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SESSION 1 Biodegradation and Chemical Treatments

The dry flesh was pushed into a clean 25 ml vial with a glass rod, and 20 ml 10% aqueous HCl added. The tissue was left to soak for four weeks at room temperature. The solution from each vial was then drawn out with a plastic syringe, and passed through a 0.45 micron millipore filter into a clean vial. The filtered solution was analysed for copper, chromium and arsenic using a GBC Integra XM sequential ICP spectrophotometer. Standards were run every 4-6 samples to confirm the absence of any significant drift during the course of the analytical work. Detection limits in the extracts were 0.3 ppm for arsenic, 0.05 ppm for chromium and 0.05 ppm for copper. Replicates with readings below these values were considered to be zero in further calculations.

A number of factors were identified that could influence results. Firstly, it is important to note that the simple extraction procedure used in this study does not involve total dissolution of organic matter, and hence may not have removed all of the copper, chromium and arsenic from the barnacle tissue. Also, boats are often moored at these piles, so antifouling paint may have contributed to the copper content of the barnacles. All piles of course were subject to this variable. CCA traces could also have been extracted from the barnacles by the 70% ethanol in which they were stored. To determine if copper, chromium and arsenic was present in the ethanol solution, excess ethanol was collected after dissection of 14 different barnacle samples (9-10 ml), filtered through 0.45 micron millipore filter into a clean vial, and oven dried overnight at 105°C. To each vial 10 ml 10% HCl was added and solution analysed. While chromium and arsenic from the ethanol solution were both below detectable levels, 22% of the copper found in both soft tissue and the ethanol was present in the ethanol. Also, only small quantities of crustacean soft tissue was extracted in this study, and no attempt was made to concentrate the analyte elements. Consequently, some of the barnacle extracts, particularly from the untreated and PEC-treated piles, contained arsenic and chromium levels below or close to the detection threshold.

The results were examined using an analysis of variance, and differences were considered significant when $p < 0.05$.

RESULTS

Barnacle coverage of piles

At Bundaberg, the piles were divided evenly amongst two sites (A and B) in the same river. Therefore, there were three replicates of each treated pile and two replicate *S. glomulifera* piles at each Bundaberg site. Barnacle cover was not estimated at site B near the river mouth, because the tidal zone surface of those piles was mostly devoid of fouling. Wave action at site B is often extreme, so that the abrasive action of mooring ropes and boats effectively keep the piles clean. Results from site A are presented, but were not statistically analysed on their own due to low replication (Tables 2 and 3).

Perhaps surprisingly, least barnacle coverage was found on the untreated *S. glomulifera* piles when the combined data from all ports were examined. Coverage was particularly low after two years (combined mean 38% cover) (Table 2). Barnacle cover was also low at the four year inspection (combined mean 50%) (Table 3). The reason for low coverage at the two year inspection is that *S. glomulifera* piles were installed with bark intact. While barnacles settled the bark free surface of *S. glomulifera* piles heavily (up to 90 % coverage), much less (about 5-10 %) coverage occured on the fibrous bark. The mean of such extremes is presented in Tables 2 and 3, so this difference produced high standard deviations for the *S. glomulifera* piles. Most of the bark was still present in the tidal zone at two years. After four years, however, *S. glomulifera* piles at all sites had lost bark in the tidal zone, so that settlement was higher. Counteracting the loss of bark, was the high degree of *Sphaeroma* sp. attack in the mid-tide region at Townsville and Cairns. This marine borer competes for space with barnacles on timber piles. Consequently, piles heavily infested with *Sphaeroma* are often almost devoid of barnacles in the tidal zone.

For the treated piles, differences in the level of barnacle coverage were not great. However, results at the two year inspection suggest that double treated *P. elliottii* piles generally have lower initial coverage than the other treated piles (Table 2). This seemed to be due to the higher levels of crud (hardened exudate of creosote from PEC) found on the piles. Streaks of crud often extended into the tidal zone, and were not settled by barnacles. Conversely, crud was either absent or light on PEC and double treated eucalypt piles. Interestingly, PEC treated *E. maculata* piles generally had highest barnacle coverage.

Mean barnacle coverage on all piles at Townsville was generally higher on the four year inspection than the two year inspection, while at Cairns the reverse was observed. At Bundaberg the degree of coverage was mostly similar for both inspections.

Copper, chromium and arsenic content of barnacles from Townsville

The mean concentration of copper, chromium and arsenic found in barnacles collected from each pile type during the two and four year inspections are shown in Table 4. Results are expressed in terms of µg of metal or metalloid per gram of oven dry barnacle soft tissue. An analysis of variance was used to determine if the concentrations in barnacles was different between the two inspections (Table 4). A similar analysis was used to determine if there were any differences between pile types at each inspection, and at both inspections combined. Barnacles collected at the two and four year inspections were a maximum of two years old. For the comparison between different piling types, the results for untreated *S. glomulifera* and PEC treated *E. maculata* piles were combined to improve the replication for statistical analysis. The combined results for these two pile types are referred to as the 'non-CCA' piles.

Arsenic

The extractable arsenic content of barnacles between the different pile types at both the two and four year inspections were not statistically significant different (Tables 5 and 6), although the results suggest a trend of higher arsenic content in barnacles from some of the CCA-treated pile types. Also, for each pile type there was no significant difference in arsenic levels in barnacles between the two and four year inspections (Table 4). However, when results for the two and four year inspections are combined

(Table 7), some differences appear. Barnacles from both the CCA-treated *P. elliottii* piles and the CCA-treated *E. maculata* piles had significantly higher levels of arsenic in their soft tissues than barnacles from the other pile types.

Chromium

At the two year inspection, there was no significant difference in the levels of chromium found in barnacles from the various pile types (Table 5). However, at the four year inspection when no detectable chromium was found in barnacles from the non-CCA piles, only barnacles from double treated *E. maculata* piles were not significantly different to the control group (Table 6). Highest chromium levels were found in barnacles from the double treated *P. elliottii* piles and the CCA-treated *E. maculata* piles (Table 6). As for arsenic, chromium levels did not drop significantly over the two to four year inspections for those piles containing CCA (Table 4). When results for the two and four year inspections are combined (Table 7), the chromium levels in barnacles from both double treated eucalypt piles (*E. maculata* and *E. pilularis*) are not significantly different to those obtained from non-CCA piles. However, barnacles collected from the remaining CCA-treated piles all have significantly higher levels of chromium in them than barnacles from non-CCA piles.

Copper

Variations were more obvious in the levels of copper found in barnacles from each pile type and inspection. Only the double treated *E. pilularis* piles had barnacles with copper levels similar to barnacles from non-CCA piles, at both the two and four year inspections (Tables 5 and 6). Up to 12 times higher copper levels were found in barnacles collected from the treated *P. elliottii* piles than were found on the non-CCA piles (Tables 5 and 6). The level of copper found in barnacles collected from double treated *E. maculata* piles was lower at the four year inspection than two year inspection. No other pile type showed a significant trend. However, if the results for all piles containing CCA (including double treated piles) are combined, the barnacles from the four year inspection have less copper in them than those from the two year inspection (Table 4). When the result from both inspections are combined, we find that all CCA-treated and double treated piles have significantly higher levels of copper in barnacles growing on their surfaces than on non-CCA piles (Table 7).

DISCUSSION

There are many environmental issues to consider when selecting piling materials for use in the sea. All materials have an environmental cost at some point. Timber wins over other materials such as steel and concrete in its manufacturing stage because it is renewable and requires less energy to produce. However, the use of treated timber may create a problem in the sea due to the leaching of toxic components. All heavy metals become toxic at some threshold availability, yet many play a vital role in metabolism (Rainbow, 1987). Antifouling paints come under particular scrutiny, because they are designed to release biocides into the environment at a rate that is toxic to adjacent fouling organisms. Therefore, antifouling paints on boats are usually replenished annually. For tributyltin oxide based paints, this strategy resulted in the build up in certain waters of tributyltin oxide to harmful levels for oysters and fish (Batley *et al.*, 1989). The strategy is different however in marine wood preservation. Service lives of at least 20 to 30 years are sought from the one application (or double application) of preservative. After this time, at least half to three quarters of the original retention of preservative must generally remain in the wood for it to have been an effective treatment. For example, four *E. macrorhyncha* F. Muell. ex Benth. natural rounds treated for a small specimen test with low temperature creosote (Barnacle and Cookson, 1990) to an average retention of 255 kg/m^3 were recently analysed. After 22 years exposure at Kwinana near Perth the specimens were still serviceable, and 68% of the original creosote could be removed from the samples by Dean and Stark soxhlet extraction (Cookson, unpublished data).

The presumed low rate of preservative leaching from treated wood in our tests is consistent with the rapid colonisation of the treated piles after installation. Piles were examined within three weeks of installation, and barnacles and algae were found on most. This rate of colonisation compares with that of a surface coated with antifouling paint that is designed to release at least nine micrograms of copper per cubic centimetre per day to control *Balanus* sp. (Cristie and Dalley, 1987). Our comparison of barnacle growth on piles was made two and four years after installation, when differences in coverage between the different piles was small, though sometimes significant. Comparisons made after shorter exposure times might have revealed greater differences. Weis and Weis (1996) found reduced diversity of fouling organisms on CCA-treated wood compared to untreated wood after one and two month exposures. After three months' exposure there was no significant difference in population, although growth of some fouling species appeared stunted. Sturgess and Pitman (1996) also found that CCA-treated wood inhibited the early colonisation of wood surfaces by marine microorganisms. The reduced colonisation on CCA-treated surfaces may be due to leaching of CCA. Our results suggest that copper is the main element accumulated by barnacles on the surface of CCA-treated piles. This is consistent with the findings of Warner and Solomon (1990) and Weis *et al.* (1991). Another factor that might reduce fouling on CCA-treated timbers compared to untreated controls, is that the preservative makes wood fibres less palatable to some microorganisms that might otherwise become a part of the fouling community of untreated wood. Corroding steel piles, and mooring pile runner pipes attached to the Townsville piles, often had reduced barnacle and fouling growth, presumably due to the leaching of iron.

When barnacles from Townsville were analysed for copper, chromium and arsenic content, perhaps not surprisingly, the results seem to relate closely to the original CCA retention of the pile. Both species of double treated eucalypt had lowest CCA retentions, and the copper, chromium and arsenic content of barnacles collected from their surfaces was often not significantly different to that of the non-CCA piles. Higher CCA retentions occured in both the *E. maculata* piles and *P. elliottii* piles treated with CCA alone, and these piles often had significantly higher levels of copper, chromium and arsenic in their associated barnacles than the non-CCA pile controls. Eucalypts treated with CCA alone have not been recommended as marine piles in the tropics, based on their widespread poor performance against teredinid borers (Cookson, 1987). Similarly, CCA-treated softwood piles generally fail to give adequate service lives in the tropics due to attack by species of *Sphaeroma*. It is possible that for double treated timbers, the creosote component reduces leaching of CCA, however, this could not be determined here.

The results suggest that the leaching of arsenic from CCA and double treated piles did not unduly increase the arsenic content of barnacles after two and four years' exposure. Some marine organisms have a high background level of arsenic. Mackay *et al.* (1975) found just 1.14 μg/g wet weight in oysters from NSW, while at Townsville we found about 19 μg/g dry mass or about 130 μg/g wet mass on non-CCA piles. Stalker and Cornwell (1975) give figures for marine crustaceans of 30 to 130 μg/g dry mass arsenic. The mean range of arsenic found in a variety of crustaceans range from about 8 to 179 μg/g dry mass (Phillips, 1990). The highest arsenic level found in barnacles on the treated piles was 94 μg/g dry mass.

Higher levels of chromium were found in barnacles from some of the piles, although this difference was not statistically significant at the two year inspection. Of the active ingredients in CCA, chromium appears most leach resistant (Leightley, 1987). Weis *et al.* (1993) found higher chromium levels in barnacles collected from CCA-treated pine, while mussels collected from the same timbers displayed no significant increase to detectable background levels.

In Dulas Bay where there is a pollution problem from copper, barnacles can have 3000 μg copper/g dry mass (Rainbow, 1987). At most other sites examined, copper levels ranged from 0.4 to 913 μg/g (Rainbow, 1987). In Hong Kong waters, copper in *Balanus* ranged from 116 to 3472 μg/g (Phillips and Rainbow, 1988). The highest levels found on piles at Townsville were 1247 μg/g for double treated *P. elliottii* piles and the lowest 265 μg/g for double treated *E. pilularis* piles.

Creosote may also cause some environmental problems in the sea. The main problem occurs shortly after pile installation. As wood absorbs moisture and swells, creosote can be forced from the piles, and indeed small oil slicks were noticed arising from some piles (mainly double treated *P. elliottii* piles) within one to two weeks of installation. Once wood swelling stabilises, the piles do not produce an oil slick. Creosote can be degraded by certain bacteria (Belas *et al.*, 1979; Drisko *et al.*, 1962). On aged piles, these bacteria may exist within the fouling community, and degrade excess creosote that nears the surface of the pile.

Of the treated pile types examined that contain CCA, double treated eucalypts caused least alteration to the natural background levels of copper, chromium and arsenic in barnacles.

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Table 1.
Timber species and preservative pile types in mooring pile study at three ports. Mean retentions are for the outer 5 mm case of the piling sapwood, and are given as % m/m of oven dry wood, and as kg/m^3 of air dry wood. PEC retentions are based upon the creosote component of the PEC.

Timber species	CCA retention % m/m	CCA retention kg/m^3	Creosote ret'n % m/m	Creosote ret'n kg/m^3
E. maculata	1.6	42	11.4	108
E. pilularis	2.0	49	17.3	153
P. elliottii	8.0	170	26.1	200
P. elliottii	5.1	108	-	-
E. maculata	2.5	66	-	-
E. maculata	-	-	17.5	167
S. glomulifera	-	-	-	-

Table 2.
Mean percentage of pile surface covered with barnacles on mid-tide downstream face at three ports after two years. Means with similar letters within a column are not significantly different ($p < 0.05$).

Timber species	Preservatives	Bundaberg, Site A	Townsville	Cairns	Mean (sd) for all sites
E. maculata	CCA + PEC	50	58 bc	75 b	64 (13) bc
E. pilularis	CCA + PEC	65	68 cd	82 b	73 (13) c
P. elliottii	CCA + PEC	42	47 b	65 ab	53 (14) b
P. elliottii	CCA	52	65 cd	82 b	69 (15) c
E. maculata	CCA	50	77 d	77 b	72 (12) c
E. maculata	PEC	68	62 c	82 b	71 (13) c
S. glomulifera	Nil	55	20 a	48 a	38 (37) a

Table 3.
Mean percentage of pile surface covered with barnacles on mid-tide downstream face at three ports at the four year inspection. Means with similar letters within a column are not significantly different ($p < 0.05$).

Timber species	Preservatives	Bundaberg, Site A	Townsville	Cairns	Mean (sd) for all sites
E. maculata	CCA + PEC	60	73 a	43 ab	55 (18) ab
E. pilularis	CCA + PEC	67	82 a	61 bc	68 (14) bc
P. elliottii	CCA + PEC	50	80 a	42 ab	53 (20) ab
P. elliottii	CCA	72	80 a	55 bc	67 (16) bc
E. maculata	CCA	62	70 a	38 a	53 (17) ab
E. maculata	PEC	80	83 a	68 c	75 (15) c
S. glomulifera	Nil	70	83 a	24 a	50 (31) a

Table 4.
Mean level of copper, chromium and arsenic present in barnacles collected from timber piling on the 2 and 4 year inspections at Townsville. Also shows the probability that results for year 2 and 4 are not significantly different. Results given in μg/gm dry mass.

Timber species	Preservative	Element	Year 2	Year 4	Prob.
E. maculata	CCA + PEC	As	28	46	0.52
E. pilularis	CCA + PEC	As	46	45	0.99
P. elliottii	CCA + PEC	As	34	58	0.14
P. elliotti	CCA	As	67	53	0.75
E. maculata	CCA	As	93	94	0.98
E. maculata	PEC	As	26	26	0.99
S. glomulifera	none	As	17	20	0.91
E. maculata	CCA + PEC	Cr	24	12	0.31
E. pilularis	CCA + PEC	Cr	43	41	0.94
P. elliottii	CCA + PEC	Cr	77	91	0.75
P. elliottii	CCA	Cr	87	39	0.56
E. maculata	CCA	Cr	94	88	0.88
E. maculata	PEC	Cr	5	0	0.08
S. glomulifera	none	Cr	16	0	0.36
E. maculata	CCA + PEC	Cu	822	345	0.03*
E. pilularis	CCA + PEC	Cu	404	265	0.08
P. elliottii	CCA + PEC	Cu	1247	692	0.09
P. elliottii	CCA	Cu	1137	1057	0.74
E. maculata	CCA	Cu	759	535	0.25
E. maculata	PEC	Cu	95	71	0.22
S. glomulifera	none	Cu	111	69	0.14
All timbers	CCA or CCA + PEC	Cu	876	567	0.01*

*Statistically significant difference ($p < 0.05$)

Table 5. Difference between barnacles on pile types after two years' exposure. Means joined by vertical line are not significantly different. Results given in µg/gm dry mass. *Non-CCA piles combined.

Arsenic

Pile type	Mean
Untreated *S. glomulifera** + PEC *E. maculata**	22
CCA + PEC *E. maculata*	28
CCA + PEC *P. elliottii*	30
CCA + PEC *E. pilularis*	46
CCA *P. elliottii*	67
CCA *E. maculata*	93

Chromium

Pile type	Mean
Untreated *S. glomulifera* + PEC *E. maculata*	9
CCA + PEC *E. maculata*	24
CCA + PEC *E. pilularis*	43
CCA + PEC *P. elliottii*	77
CCA *P. elliottii*	87
CCA *E. maculata*	94

Copper

Pile type	Mean
Untreated *S. glomulifera* + PEC *E. maculata*	101
CCA + PEC *E. pilularis*	404
CCA *E. maculata*	759
CCA + PEC *E. maculata*	822
CCA *P. elliottii*	1137
CCA + PEC *P. elliottii*	1247

Table 6. Difference between barnacles on pile types at four year inspection. Means joined by vertical line are not significantly different. Results given in µg/gm dry mass. *Non-CCA piles combined. **Below detectable limits

Pile type	Mean
Arsenic	
Untreated *S. glomulifera** + PEC *E. maculata**	23
CCA + PEC *E. maculata*	43
CCA + PEC *E. pilularis*	45
CCA *P. elliottii*	53
CCA + PEC *P. elliottii*	58
CCA *E. maculata*	94
Chromium	
Untreated *S. glomulifera* + PEC *E. maculata*	0**
CCA + PEC *E. maculata*	12
CCA *P. elliottii*	39
CCA + PEC *E. pilularis*	41
CCA *E. maculata*	88
CCA + PEC *P. elliottii*	91
Copper	
Untreated *S. glomulifera* + PEC *E. maculata*	71
CCA + PEC *E. pilularis*	265
CCA + PEC *E. maculata*	345
CCA *E. maculata*	535
CCA + PEC *P. elliottii*	692
CCA *P. elliottii*	1057

Table 7.
Difference between barnacles on pile types determined when results for both two and four year inspections are combined. Number = combined number of piles analysed. Means joined by vertical line are not significantly different. Results given in µg/gm dry mass. *Non-CCA piles combined.

Arsenic

Pile type	Number	Mean			
Untreated *S. glomulifera** + PEC *E. maculata**	20	19	│		
CCA + PEC *E. maculata*	10	36	│	│	
CCA + PEC *P. elliottii*	11	43	│	│	
CCA + PEC *E. pilularis*	12	45	│	│	
CCA *P. elliottii*	11	61		│	│
CCA *E. maculata*	11	93			│

Chromium

Pile type	Number	Mean				
Untreated *S. glomulifera* + PEC *E. maculata*	20	5	│			
CCA + PEC *E. maculata*	10	18	│	│		
CCA + PEC *E. pilularis*	12	42	│	│	│	
CCA *P. elliottii*	11	65		│	│	│
CCA + PEC *P. elliottii*	11	84			│	│
CCA *E. maculata*	11	91				│

Copper

Pile type	Number	Mean			
Untreated *S. glomulifera* + PEC *E. maculata*	20	86			
CCA + PEC *E. pilularis*	12	334	│		
CCA + PEC *E. maculata*	10	584	│	│	
CCA *E. maculata*	11	657		│	
CCA + PEC *P. elliottii*	11	995			│
CCA *P. elliottii*	11	1101			│

TREATMENT OF EUCALYPT PALING FENCE TIMBERS WITH EMULSIONS OF CREOSOTE AND CCA

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ABSTRACT

Unseasoned fencing timbers of *Eucalyptus regnans* F. Muell. (mountain ash) and *E. obliqua* L'Herit. (messmate) were treated with PROCCA and PEC. Rails were treated using four different schedules. Three of the schedules, alternating pressure method (APM), presteaming plus 2 h Bethell, and 4 h Bethell, gave similar retentions of PEC in both *E. regnans* and *E. obliqua.* The remaining schedule, 2 h Bethell only, gave the lowest retentions. While presteaming increased retentions, this procedure caused greater collapse and checking than the other treatments, especially to *E. regnans*. The trend for PROCCA appeared similar to PEC. Up to 40% of the cross section of *E. regnans* rails was penetrated with PROCCA, while *E. obliqua* was more difficult to treat. Unseasoned sapwood was readily penetrated. After six months in the accelerated field simulator, untreated post ends of *E. regnans* and *E. obliqua* had 1 to 2 mm depth of decay, while all treated post ends and untreated *E. camaldulensis* Dehnh. controls were sound. Most blocks cut from PEC treated rails and palings resisted fungal colonisation in a laboratory decay test, while most blocks from PROCCA treated timbers had fungal growth on the surfaces exposed after docking.

INTRODUCTION

The traditional hardwood fence usually has posts cut from naturally durable timbers such as river red gum (*Eucalyptus camaldulensis* Dehnh.), and palings, rails and plinths cut from timbers of low natural durability such as *Eucalyptus regnans* F. Muell. (mountain ash) and *E. obliqua* L'Herit. (messmate). Because the fence is untreated, palings, rails and plinths often need replacing within fifteen years' service. Such lack of durability has been exploited by the hardwood industries' competitors, so that treated pine and steel have made large inroads into the fencing market.

The aim of this project was to produce a coloured preservative treatment that will enhance the aesthetics and durability of the hardwood fence. The project also examines whether *E. regnans* and *E. obliqua* can replace *E. camaldulensis* for fence posts. Discussions with the Timber Promotion Council indicated that the treatment would need to be applied to timbers that were unseasoned. The preservatives selected were PROCCA (Tanalith Gold) and PEC-brown, because it was thought that these oil containing preservatives would enhance weathering characteristics and reduce nail corrosion.

We expected that any treatment would produce only thin side grain penetration in the heartwood, so are examining various pre-machining options and construction practices that might extend the durability of the treated fence. One option is that

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timbers should be cut to standard lengths, and posts prenotched and profiled before treatment. The fence could then be erected in modular fashion, without the need to break the treatment envelope during construction. If alterations are necessary, some of the timber species/preservative combinations might be more able to withstand a limited amount of docking and notching after treatment. A field exposure trial, and the laboratory decay test described here, have been set up to examine the effect of machining after treatment. The in-ground portion of *E. regnans* and *E. obliqua* fence posts are likely to require additional protection to that of the above ground portions of the fence. Hence, the effects of incising and bottom end slotting of posts to improve preservative uptake are also being examined. Furthermore, a method of fixing rails to posts with fencing wire rather than by notching will be examined, and may result in the use of thinner posts. This paper presents treatment and penetration results, and an update of some of the exposure trials.

TREATMENTS AND RETENTIONS

Timber material

Eucalyptus regnans fencing components were supplied by Bonang Timbers Pty Ltd of Nowa Nowa, Vic. *E. obliqua* was supplied by Eureka Timber Company of Ballarat, Vic. The mean cross section of timbers used in the study are given in Table 1. Timber packs were stored under plastic sheeting until required.

Table 1. Timber sections used in study, and their mean moisture content prior to treatment.

Timber species	Approximate timber cross section in mm (and mean M.C.)			
	Posts	'Thin' posts	Rails	Palings
E. regnans	125 x 75 (94%)	100 x 75 (78%)	76 x 37 (101%)	100 x 20 (93%)
E. obliqua	120 x 70 (78%)	90 x 70 (80%)	75 x 35 (66%)	90-100x14 (68%)

Timbers were selected from the packs within three days before treatment. Both ends of all timber lengths were cut, and brushed with dimethyl yellow to determine sapwood/heartwood boundaries. There was less sapwood in the *E. regnans* material than the *E. obliqua* material. The dimensions of each test piece for treatment was recorded. Immediately adjacent to the test piece a block about 30 mm long was cut for moisture content (M.C.) determination (Table 1). Timbers were weighed before and after treatment to determine preservative retentions.

Some of the posts were incised before treatment. This involved sending wrapped bundles of 1.8 m long posts to the Koppers treatment plant at Grafton, NSW. After incising at Grafton, posts were again strapped, wrapped in plastic and returned to Clayton. Posts were cut into either 1.6 m, or 0.8 m lengths. Four replicates of each timber species for each preservative treatment of the 1.6 m incised posts were also prenotched, the top ends splay cut, and the bottom ends slotted before treatment. Slotting involved making three longitudinal cuts 200 mm long from the bottom end with a band saw. The slots were cut with the aim of improving preservative penetration so that a limited amount of docking could be tolerated during post installations and height adjustment.

Preservatives and treatment methods

PEC-brown contained 65% high temperature creosote and 5% brown oxide pigment. PROCCA contained 10% CCA salts and 5% oil. PEC-brown was heated to 60-75°C before treatment, while PROCCA was used at ambient temperature. Two pilot plant treatment cylinders were used. One cylinder 2.0 m long was for PROCCA treatment, while the other cylinder 2.9 m long was for PEC. Timbers were loaded into the cylinders and separated with stickers at one end near the cylinder door before treatment.

For PROCCA four different schedules were examined using 1.2 m rails (all vacuums were -90 to -100 kPa):

1. Two hour Bethell
Initial vacuum 30 mins, hydraulic pressure of 1400 kPa for 120 mins, final vacuum 30 mins.

2. Alternating pressure method (APM)
Initial vacuum for 30 mins. A pressure of 1400 kPa was then applied for 10 mins, released to atmospheric pressure for 5 mins, and then reapplied. There were 12 such pressure cycles, so that the total duration of pressure was 120 mins. Final vacuum was 30 mins.

3. Three hour steaming followed by two hour Bethell
Timber was loaded into the cylinder, and high pressure steam applied for 180 mins. The timber was then removed and allowed to cool for several hours. It was weighed, and reloaded into the cylinder for treatment. Initial vacuum was for 30 mins, 1400 kPa pressure for 120 mins, and final vacuum 30 mins.

4. Four hour Bethell
Initial vacuum 30 mins, hydraulic pressure 1400 kPa for 240 mins, final vacuum 30 mins.

For PEC the same schedules were used, except that the average pressure achieved was 1200 kPa. All remaining timbers treated with PEC-brown or PROCCA were impregnated using the four hour Bethell cycle.

Retention results

A summary of retention results are presented in Table 2. Using the 1.2 m rails, four different treatment schedules for each preservative were examined. The results were analysed using one-way ANOVA. We decided to exclude those replicates containing 30% or more sapwood from the analysis, leaving 8-10 replicates. For the PEC treatment of *E. regnans*, the 2 h Bethell schedule gave the lowest mean retention (51.7 kg/m^3). This retention was significantly lower than the mean retentions achieved for all other treatments. The 4 h Bethell schedule gave the highest mean retention (105 kg/m^3). Both the APM and the presteaming plus 2 h Bethell treatment gave similar mean retentions (74.9 and 72.9 kg/m^3 respectively). Conversely for the PEC treatment of *E. obliqua*, an analysis of variance showed that there was no significant difference between the retentions obtained using the four different treatment schedules. When results for both *E. regnans* and *E. obliqua* are combined, the 2 h Bethell was again shown to have lowest mean retention (52.0 kg/m^3). However, the mean retentions obtained with the other three schedules, APM (78.7 kg/m^3), presteaming plus 2 h Bethell (78.7 kg/m^3) and 4 h Bethell (89.6 kg/m^3), were not significantly different.

Both the PROCCA treatment of *E. regnans* and *E. obliqua* showed there was no significant difference in mean retention obtained by the four different treatment schedules. However, when both timber species are combined and compared, the mean CCA retention obtained from the 2 h Bethell (5.5 kg/m^3) was significantly different to the presteaming plus 2 h Bethell (9.1 kg/m^3), but not the APM (7.0 kg/m^3) or 4 h Bethell (7.4 kg/m^3).

Rails removed from the PEC treatment cylinder after steam conditioning showed signs of warp and collapse. At first, this effect did not occur for timbers from the PROCCA treatment cylinder. Perhaps steaming conditions in this cylinder were less harsh. However, after the PROCCA treated rails had seasoned, the presteamed timbers had greater collapse and checking than those treated using the other schedules. This difference was more obvious for *E. regnans* than *E. obliqua*.

Palings 1.2 m long treated with PEC-brown achieved mean PEC retentions of 120 kg/m^3 for *E. regnans* and 164 kg/m^3 for *E. obliqua* (Table 2). PEC contains 65% creosote, thus mean creosote retentions of 78 kg/m^3 and 107 kg/m^3 respectively were achieved. PROCCA contained 10% CCA, therefore *E. regnans* palings had a mean of 10.5 kg/m^3 CCA, and *E. obliqua* 11.8 kg/m^3 CCA. A higher proportion of sapwood in the *E. obliqua* material than the *E. regnans* material probably accounts for their higher mean preservative retentions. The above-ground H3 retention requirement for hardwoods is approximately 79 kg/m^3 for creosote and 10.4 kg/m^3 for CCA salt (AS 1604-93). While many palings met these retention requirements, few would meet the penetration requirements (see penetration results).

The surfaces of PROCCA treated timbers were touch dry soon after treatment. However, the PEC treated timber surfaces were still moderately wet with creosote oil three weeks after treatment. Treatment was performed during winter. In summer, surfaces would dry more quickly. Natural round eucalypt posts from another project were treated at a similar time as the fencing timbers, using the standard PEC white formulation (containing 3.5% white pigment). These dried more quickly than the sawn fencing timbers.

PENETRATION STUDIES

Some of the timbers have been or are in the process of being examined for preservative penetration. Some of the post sections were treated as 0.8 m lengths. After treatment, they were cut in half to produce 0.4 m specimens for a Walpeup termite field test, and the AFS exposure. Those treated with PROCCA were sprayed on the freshly cut surface with chromazurol solution (AS 1605-1974) to detect the presence of copper. Those 0.8 m specimens treated with PEC were placed in a freezer for three weeks prior to cutting, so as to reduce creosote bleeding. They were photographed within five minutes of cutting.

An examination of the penetration patterns in posts from both species showed that sapwood corners when present were penetrated by the preservatives, even though the timber was unseasoned. The side grain penetration into the heartwood of both timbers was mostly 0.5-1 mm deep, including the side grain around the incisions. However, many of the vessels in the *E. regnans* posts were treated due to end grain penetration. Deep vessel penetration was more limited in *E. obliqua.*

In order to quantify penetration in the PROCCA treated rails, we used the method described by Saunders (1982) and Ladu *et al.* (1995). This involved laying a grid of dots drawn on a transparent sheet over the end grain of specimens. The number of dots overlapping the indicated penetration patterns are then counted, and used to derive a percentage treated cross section out of the total number of dots fitting the cross section. Percentage penetrations were measured on surfaces docked 100 mm and 600 mm from the ends of the 1.2 m rails.

The penetration results for the PROCCA-treated rails (Table 3) were mostly consistent with retention results (Table 2). For *E. regnans* the penetration results show that the 2 h Bethell treatment delivered least preservative into wood. The APM, presteaming plus 2 h Bethell, and 4 h Bethell schedules produced higher penetrations, with means that were not significantly different. The presteaming plus 2 h Bethell treatment tended to produce the highest mean retentions, with about 40% of the cross section penetrated with the copper from PROCCA. As might be expected, there was also a trend where less preservative was found near the centre of the rails than near the ends. *E. obliqua* heartwood was much more difficult to treat than *E. regnans* heartwood, with means of only 1 to 8 % of the cross sections penetrated.

ACCELERATED FIELD SIMULATOR ASSESSMENT

An accelerated field simulator trial is being conducted on treated post ends. Five replicates of each post type, timber species and preservative were installed. Untreated *E. camaldulensis* post ends were included for comparison. Specimens are 400 mm long, distributed between two soil troughs, and buried 300 mm into 'Toolangi forest loam'. General details of the soil and test procedure can be found in the article by Cookson (1994). This project will provide a useful comparison of preservative treated posts in the AFS, and in field tests at both Clayton and Walpeup.

After six months in the AFS, a limited amount of decay was found in just the untreated *E. regnans* and *E. obliqua* posts (Table 4). All treated posts and the untreated *E. camaldulensis* posts were sound.

LABORATORY DECAY TEST

The laboratory decay test was designed to investigate whether palings and rails could resist decay after being docked to length. Eight replicate palings and rails of each preservative and timber species were sampled. Heartwood blocks 30 mm long were cut from the 1.2 m palings and rails. The blocks were either 'end' blocks cut 100 to 160 mm from the ends of specimens, or 'centre' blocks cut from the central 100 mm portion of the specimens. Three replicate end and centre blocks were cut from each paling or rail, with one replicate destined for exposure to either the white rot fungus *Perenniporia tephropora* (DFP 7904), the brown rot fungus *Coniophora olivacea* (DFP 1779), or to act as a sterile control. The blocks were artificially weathered, and exposed to decay fungi using procedures similar to that described by Cookson and Dougal (1993), except that the end grain of blocks was not coated with epoxy. In this method, blocks were placed in trays containing fungus (except sterile control trays) on malt agar, covered with aluminium foil and placed in plastic bags for incubation. After 16 weeks, the trays were uncovered and the level of fungal growth on each block recorded. Blocks were then removed and are now conditioning to constant mass to enable mass loss determinations.

The mass loss figures are not yet available, however, the level of fungal growth observed on each block gives an indication of performance. Tables 5 and 6 show the mean percentage fungal cover observed on the two docked faces of each block. The untreated *E. regnans* and *E. obliqua* were fully or mostly covered in fungal growth. Some noteworthy findings were that untreated *E. regnans* was heavily decayed, especially by the white rotting fungus. Untreated *E. obliqua* has little if any decay, and is moderately durable. *C. olivacea* was more sensitive to creosote than *P. tephropora*, and failed to grow on most creosote treated blocks. Creosote treated timber suffered less decay after docking than the PROCCA treated timber. This may be due to the bleeding of creosote across the docked surface of blocks when they were cut.

CONCLUSIONS

While the project is in its early stages, results so far suggest that green *E. obliqua* and *E. regnans* can be treated with either PEC or PROCCA sufficient to protect sapwood, and that treatment will provide added protection to heartwood. Treatment of rails and palings should extend service life compared to the same untreated components in the traditional hardwood fence. Early results suggest that palings and rails treated with PROCCA should be precut to final dimensions to avoid docking after treatment. PEC treated rails and palings may be able to withstand a limited amount of docking after treatment, as creosote tends to bleed across freshly cut surfaces to partially renew the antifungal barrier. The work is at a stage too early to suggest whether treated posts could replace untreated *E. camaldulensis* posts.

ACKNOWLEDGMENTS

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Table 2. Summary of retention results in kg/m^3, based on total volume of piece. Showing mean (and standard deviation). PEC retentions are for whole PEC, and PROCCA retentions are for CCA salt.

Treatment schedule	Profile, length	No. of replic.	PEC		PROCCA	
			E. regnans	*E. obliqua*	*E. regnans*	*E. obliqua*
2h Bethell	Rail, 1.2m	9-10	51.7 (17.2)	52.2 (15.2)	5.5 (1.4)	5.4 (2.7)
APM	Rail, 1.2m	8-10	74.9 (29.2)	82.9 (40.5)	8.6 (35)	5.1 (3.0)
Steam + 2h Bethell	Rail, 1.2m	9-10	72.9 (18.0)	84.5 (16.3)	10.1 (4.3)	8.1 (4.2)
4h Bethell	Rail, 1.2m	10	105.0 (25.3)	74.2 (43.0)	8.8 (5.2)	6.0 (2.6)
"	Rail, 1.6m	3	60.9 (14.2)	58.3 (34.7)	6.6 (1.8)	6.1 (4.5)
"	Plinth1.6m	1	86.6	95.0	6.3	9.7
"	Thin post, 1.6m. I,S	4	95.2 (24.8)	50.9 (4.9)	13.1 (0.7)	5.0 (0.3)
"	Post, 1.6m I	4	87.5 (31.0)	65.4 (9.1)	10.2 (1.3)	5.1 (1.3)
"	Post, 1.6m I,S,N	4	72.3 (20.4)	104.2 (21.4)	8.7 (3.3)	6.0 (2.3)
"	Post, 1.6m plain	4	-	-	11.1 (3.9)	2.8 (0.4)
"	Post, 0.8m I	8	92.0 (19.7)	57.7 (28.7)	8.7 (3.7)	5.6 (1.4)
"	Post, 0.8m I,S	8	130.9 (28.2)	98.7 (10.0)	9.8 (3.7)	6.6 (2.0)
"	Post, 0.8m plain	5	59.8 (25.3)	53.5 (17.1)	5.3 (1.9)	3.1 (0.7)
"	Paling, 1.3m	12	108.9 (29.6)	96.1 (33.0)	11.1 (2.7)	10.0 (5.7)
"	Paling, 1.2m	36-44	120.2 (38.9)	163.5 (58.5)	10.5 (2.9)	11.8 (7.0)

For posts, I = incised, S = end cut slots at one end (1.6 m posts) or both ends (0.8 m posts), N = prenotched for rails to be fitted.

Table 3. Penetration in PROCCA-treated 1.2 m rails. The percentage of a cross section (100 mm and 600 mm from ends) with positive indication for copper. Mean (standard deviation) of eight replicates.

Timber species	**Distance from end**	**Percentage cross section with indication of copper**			
		2 h Bethell	**APM**	**Steaming + 2 h Bethell**	**4 h Bethell**
E. regnans	100 mm	13.3 (11.7)	32.2 (23.7)	41.8 (26.6)	30.0 (29.3)
E. regnans	600 mm	8.2 (6.0)	26.9 (22.7)	39.8 (22.7)	21.8 (27.3)
E. obliqua	100 mm	3.7 (5.8)	3.3 (7.5)	7.6 (8.8)	6.6 (8.6)
E. obliqua	600 mm	1.5 (2.3)	1.7 (3.2)	4.4 (7.1)	1.4 (3.8)

Table 4. Depth of decay found in 400 mm long post ends after six months exposure in the AFS.

Timber species	Treatment	Depth of soft rot after 6 months		
		Plain	Incised	Incised + slotted
E. regnans	None	2 mm	-	-
E. regnans	PROCCA	0 mm	0 mm	0 mm
E. regnans	PEC	0 mm	0 mm	0 mm
E. obliqua	None	1 mm	-	-
E. obliqua	PROCCA	0 mm	0 mm	0 mm
E. obliqua	PEC	0 mm	0 mm	0 mm
E. camaldulensis	None	0 mm	-	-

- not in test.

Table 5. Percentage of surface on cut end grain faces of paling blocks covered by fungus. Mean (standard deviation) of 16 faces on eight blocks.

Fungus	Preservative	Position	*E. regnans*	*E. obliqua*
Brown rot *C. olivacea*	None	Any	91 (25)	81 (35)
	PROCCA	End	89 (22)	64 (42)
		Centre	68 (34)	87 (29)
	PEC	End	0 (0)	0 (1)
		Centre	1 (2)	1 (2)
White rot *P. tephropora*	None	Any	100 (0)	100 (0)
	PROCCA	End	97 (4)	96 (8)
		Centre	96 (5)	100 (1)
	PEC	End	16 (24)	33 (36)
		Centre	31 (30)	40 (38)

Table 6. Percentage of surface on cut end grain faces of rail blocks covered by fungus. Mean (standard deviation) of 16 faces on eight blocks.

Fungus	Preservative	Position	*E. regnans*	*E. obliqua*
Brown rot *C. olivacea*	None	Any	90 (17)	82 (14)
	PROCCA	End	64 (34)	48 (37)
		Centre	47 (33)	60 (37)
	PEC	End	0 (0)	0 (0)
		Centre	0 (0)	0 (0)
White rot *P. tephropora*	None	Any	93 (25)	65 (34)
	PROCCA	End	81 (13)	71 (23)
		Centre	81 (29)	69 (23)
	PEC	End	1 (3)	0 (1)
		Centre	20 (29)	1 (3)

STUB DIFFUSION TRIAL WITH EXPERIMENTAL RODS CONTAINING DIFFUSIBLE COPPER/BORON/FLUORINE

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ABSTRACT

The diffusibility of two novel preservative rod compositions was assessed in a stub diffusion trial. Both formulations contained relatively high concentrations of boron and fluorine as their biocidal elements. In addition, one of the formulations also included chelated copper as a third component. The performance of the novel preservative rods was compared with commercially available Polesaver™ rods, which contain boron and fluorine as their active elements.

Stubs of *Eucalyptus sieberi* (Silvertop ash) were axially drilled to a depth of 250 mm and a preservative rod inserted into the drilled holes. Three, six, nine and twelve months after preservative application, three replicate stubs were split longitudinally. The extent of radial and longitudinal diffusion of active elements as shown by elemental indicators was recorded.

The performance of the experimental rods compared favourably with the commercial Polesaver™ rod. Of particular note was the successful use of copper diglycinate chelate as a source of diffusible copper. The copper component continued to diffuse throughout the trial period, without forming insoluble complexes through reaction with the boron and fluorine components. This has not been previously reported in the literature and points the way to a whole new class of wood preservative systems.

INTRODUCTION

In physico-chemical terms, the wood substance may be regarded as an ion exchange column. The anhydroglucose monomer units of cellulose contain three free hydroxyl groups, whilst lignin contains phenolic and carboxylic groups (1). These groups have at least one pair of electrons which participate in displacement reactions. As a consequence, positively charged ions (such as Cu^{2+}), when diffusing into wet timber, are readily removed from solution by covalent bonding on to the wood substance. On the other hand, negatively charged ions (such as BO_3^{3-} and F^-) are not significantly affected by these interactions and continue to freely diffuse through both heartwood and sapwood.

We hypothesised that if metal ions were chelated into water soluble complexes having a neutral or negative charge, then these neutral or negatively charged chelate complexes should diffuse through wet timber in a similar manner to borate and fluoride anions. That is to say, the chelates should provide a vehicle for introducing fungitoxic metal elements throughout a timber substrate if they were used, for instance, as part of a remedial treatment formulation.

Testing of individual water-soluble metal chelates had shown our hypothesis to be substantially correct, with selected chelates being both diffusible and fungitoxic (2). However, we did not know whether metal chelates could be effectively used in conjunction with borates and fluorides without forming insoluble precipitates and whether the chelates would continue to diffuse for the life of the preservative treatment.

We selected fungitoxic rods as the delivery method for testing our novel chelate preservative. Preschem "Polesaver ™" rods (containing boron and fluorine as the active elements) have a proven record in the ground-line protection of wooden power transmission poles. We used Polesaver™ rods as our control and prepared two sets of experimental rods to test against the Polesaver™ formulation. One set of experimental rods (the B/F rods) contained boron and fluorine as the active elements whilst the

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TREATED TIMBER FRAMING
TECHNICAL REQUIREMENTS & MARKET OPPORTUNITIES

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ABSTRACT

The ban on organochlorine termiticides is now in place. The building industry and home owners are now faced with a plethora of different options for protecting homes from termite infestation. This paper seeks to review some of the technical requirements for treated framing in Australia, including the natural durability of softwood heartwood. The opportunity to niche market differentiated products into the framing market is discussed and conclusions on the attractiveness of various preservatives drawn.

INTRODUCTION

Following the ban on organochlorine termiticides on July 1995, building industry and home owners have had to select one or more alternate termite protection methods. Broadly speaking these protection methods can be categorised into 4 different segments.

A. **Ground Spraying.** The predominant chemical being used by the Pesticide industry is the organophosphorus insecticide chlorpyrifos. Chlorpyrifos breaks down more rapidly in ground contact than organochlorines hence the need to reapply the treatment after a few years. Typical initial treatment costs for the average home are around $800-$1000. Retreatment costs are similar.

B. **Physical Protection Systems.** There are two physical systems currently marketing within Australia - Termimesh and Granitguard.

Termimesh relies on a fine stainless steel mesh around the perimeter of a slab and extending outward 300 mm. The mesh is fine enough to physically prevent termites crawling through it yet still allow drainage. Being stainless steel it is very tough and should last for many years. This of course assumes that the slab will remain intact with no allowance for termites to gain access through cracks or faults.

Consumer acceptance of Termimesh appears to be quite high with typical costs around the $1200 - $1600 for the average home.

Granitguard, a compacted basalt chip bed reportedly used extensively in Hawaii is also in use in Australia, although market penetration appears to be lower than Termimesh. Typical costs are similar to Termimesh.

C. **Naturally Termite Resistant Building Materials.** Included here are steel, concrete and naturally durable timber. Some years ago steel producers set out to become a major competitor in the house framing market. They embarked on a deliberately aggressive advertising campaign, attacking timber. They used timber's susceptibility to termite attack to advantage. Citing the durability of steel as a benefit and introducing a fear factor ie "Termites Eat Wood" into their marketing program. Today the steel industry has made significant market gains into the NSW and WA market. Market share in framing in NSW is reported to be between 10-15% and growing. Market share is lower in other states.

In North Queensland, concrete reinforced framing is widely used in cyclone prone areas, whilst naturally durable timbers (Cypress pine and select hardwoods) are used where resource is available at competitive pricing.

D. **Preservative Treated Termite Resistant Wood Fibre Products**. Here the concept is based on impregnation of a termiticide, typically a synthetic pyrethroid, into wood fibre products, thus rendering the material termite resistant. The philosophy is based on protecting those wood fibre products which are structural, hardest to inspect for infestation and hence, likely to cost the most to be replaced.

Two preservative treated products for internal use are currently sold in the marketplace. Termite resistant particleboard flooring is marketed by CSR under the Structifloor brand name. Current market penetration of the termite resistant product is around $6000m^3$. Termite resistant Structifloor has been in the market for around 7 years.

The second preservative treated product available is termite resistant softwood framing. The hazard is defined as H2 according to AS1604 - 1996 which means applications subject to termite attack but not subject to moisture and fungal decay hazard.

ANALYSIS OF PRESERVATIVE TREATED TIMBER OPTIONS

The choice of treatment options for the preservation of dry, structurally graded softwood building timber with currently available technology can be summarised as follows:

Option 1: CCA treatment of the dry rough sawn timber followed by kiln drying, gauging and structural grading.

Option 2: CCA treatment of the dried, gauged and structurally graded timber product followed by redrying.

Option 3: LOSP treatment of the dried, gauged and structurally graded timber product. Redrying would not be required.

Other water borne preservatives such as boron are currently not approved in Australia for H2 application but are subject to further development. In addition, boron use in Australia will be limited by grading requirements due to the need to redry after the typical water based application processes.

Of the the above options, option 1 would involve the generation of large amounts of treated wood waste as the gauging process would be done on the treated product. This would represent a waste of preservative as well as increasing difficulties in disposing of such waste.

Also, both option 1 or 2 would mean very significant departures from the standard process for the manufacture of the treated product which increase risks of sludging and solution stripping. Furthermore, the feasibility of the second drying in option 2 will place high demand on kiln availability effectively doubling the capacity required such that redrying to meet structural requirements can be achieved. In addition, the kiln schedules for redrying the treated timber without degrade are at lower temperature and hence slower than conventional high temperature schedules.

The LOSP option has the advantage of being able to be done on the product in the final shape and form and as it does not affect the moisture content it does not require kiln drying after treatment. Estimates for the costs of the CCA "dry after treatment" against LOSP option for H2 treatment are compared in table 1. The assumed starting stage is dry, gauged and graded timber to be treated using modern CCA or LOSP plant. The option of treating prior to gauging is not considered. (Plant depreciation has not been included in these calculations).

TABLE 1: TREATMENT COSTS FOR H2 LOSP AND CCA "DRY AFTER TREATMENT"

Process Component or Cost Item	CCA "Dry After Treatment" $\$/m^3$	LOSP H2 Treatment $\$/m^3$
Treatment chemical	\$15.00 (approx 3.5 kg CCA oxide)	\$56.00 (40 L @ \$1.40/L)
Plant operation cost	\$20.00	\$16.00
Stickering *	\$20.00	--
Kiln Drying *	\$50.00	--
De-stickering *	\$20.00	--
TOTAL	**\$125.00**	**\$72.00**

* Estimates based on information from industry sources.

The analysis in table 1 indicates a considerably lower overall cost for the LOSP. This is due to the elimination of the rehandling and redrying costs required for water borne treatments. In addition, the cost of timber degrade after re-drying has not been included in the CCA treatment cost breakdown.

OTHER BENEFITS.

The LOSP option allows the producer to run a "just-in-time" supply system. Stock would generally be held untreated as normal. When required, stock can be treated and despatched within a few days of order. With water borne treatment, due to the extra processing time there would be a much longer delay between order and supply or alternatively stocks of treated product would have to be held.

As the LOSP treatment for H2 contains no heavy metal based or residual ingredients, the potential for site contamination is very low. In addition, LOSP treatments are drip free, do not increase moisture content or require long holding times.

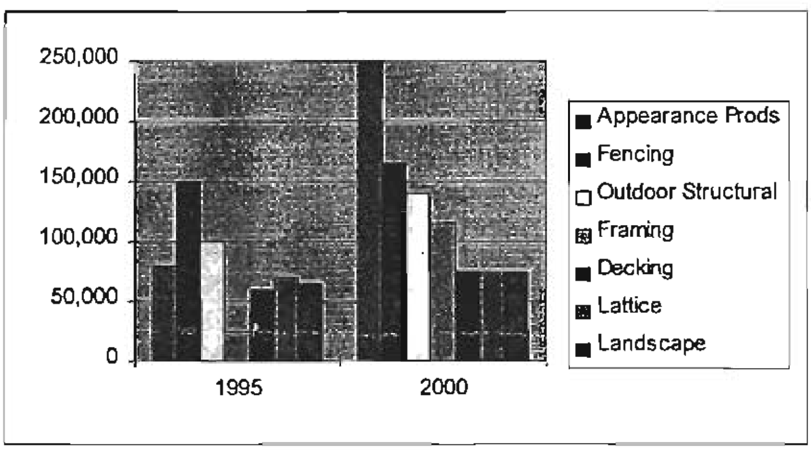
LOSP treatment can also be readily coloured to differentiate it from untreated and CCA treated timbers and can have water repellent additives included if required.

As market survey results have indicated a negative perception of CCA treated timber by builders, mainly based on experience of poor dimensional stability, the ability to treat a timber product without affecting its dimensions during treatment is important. In addition, offering protection against incidental water absorbtion during its installation, is of major benefit. Finally, LOSP treatment does not increase corrosion of the timber to the fixtures and fittings which are used with it. This is opposed to other copper containing treatments which may contribute to increased corrosion of nails and plates and necessitate use of galvanised fixings in some cases.

Of course, critical to the commercial success of any product is the potential for incorporation into current production systems. With the recent removal of limitation on unpenetrated heartwood in H2 treatment of Pinus elliottii and Pinus caribaea, the potential to improve the cost effectiveness of H2 LOSP treatment also exists. This is achieved by being able to optimise schedules which can be based on sapwood penetration only, reducing both chemical usage and post treatment holding times.

With the average cost of a treated frame house only being about $900-$1000 in comparison to the other alternatives, market expectations are that H2 termite resistant framing will become the third largest treated timber market segment in Australia by the year 2000 (Graph 1) behind fencing and outdoor structural.

Graph 1. Australian Sawn Treated Timber (m^3) - Major Segments



CONCLUSIONS:

The opportunity for a treated timber frame utilising LOSP technology is now a cost effective reality as a result of the introduction of a redefined H2 specification and considerable research into the structural and performance characteristics of the product.

In particular, LOSP treated framing offers, non metallic active systems with proven performance against termites, no structural degrade, no increase in moisture content, no dimensional changes during treatment and the option of water repellant additives for increased protection during installation. As such, this product offers one of the best defences against non timber product substitution and a substantial growth opportunity for the timber treatment industry.

PILE SURFACE COVERAGE AND COPPER, CHROMIUM AND ARSENIC CONTENT OF BARNACLES GROWING ON EXPERIMENTAL MOORING PILES

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ABSTRACT

A marine test of commercially available timber piles was established in three ports in Queensland. For treated piles after two and four years' exposure, least barnacle growth (mean of 53% of surface) in the mid-tide zone was on double treated (CCA + PEC) *Pinus elliottii* piles, while PEC treated *Eucalyptus maculata* piles had highest mean barnacle coverage (71 and 75%). Untreated *Syncarpia glomulifera* piles had low barnacle coverage due to the presence of bark. Barnacles were collected from piles at Townsville and analysed for copper, chromium and arsenic. There was no statistically significant difference in the extractable arsenic content of barnacles between the different pile types at the two and four year inspections, but some significant differences occurred when results for the two inspections were combined. Barnacles from CCA-treated and double treated piles had higher chromium and particularly copper levels than barnacles from the untreated *S. glomulifera* piles and PEC-treated *E. maculata* piles. However, differences were not always statistically significant. Of the piles containing CCA, chromium levels were lowest in barnacles from double treated *E. maculata* piles. Arsenic and chromium levels in barnacles from each pile type were similar after two and four years, whereas copper levels had generally fallen.

INTRODUCTION

Through the collaboration of CSIRO, Queensland harbour authorities, Queensland Department of Primary Industries (Forestry), and Koppers Timber Preservation, a marine test of commercially available timber piles was established at Bundaberg, Townsville and Cairns, to represent a range of conditions found in Queensland. The piles were CCA salt (copper-chrome-arsenic) treated *Eucalyptus maculata* Hook. (spotted gum), CCA-treated *Pinus elliottii* Engelm. (slash pine), PEC (pigment emulsified creosote) treated *E. maculata*, and double treated (CCA + PEC) *E. maculata, P. elliottii* and *E. pilularis* Sm. (blackbutt). Untreated *Syncarpia glomulifera* (Sm.) Niedenzu (turpentine) is the major pile type used in Australia and was included for comparison. The piles are inspected every two years for marine borer attack (Cookson and Barnacle, 1993; Cookson, 1996).

A number of studies have investigated the effect of CCA-treated timbers on marine organisms and the environment. Some studies indicate that the preservative can leach from timber at a rate that causes environmental problems (Weis and Weis, 1995), while others suggest leaching causes little change to the natural background levels of copper, chromium and arsenic (Albuquerque and Cragg, 1995; Baldwin *et al.*, 1996). The opportunity was therefore taken during inspections to assess the impact of the different commercial pile types on barnacles. The extent to which barnacles were able

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to colonise the piles was estimated at each site. Additionally at Townsville only, the copper, chromium and arsenic content of barnacles growing on the piles was determined. Barnacles are useful bioindicator species in studies of heavy metal pollution (Rainbow, 1987).

MATERIALS AND METHODS

Estimation of barnacle coverage on pile surfaces

There are forty mooring piles at each test site, comprising six replicates of each treated pile type, and four replicates of the untreated *S. glomulifera* piles (Table 1). The piles were examined during low tide for barnacle colonisation, two and four years after installation. All sites are located near the mouths of estuarine rivers. Inspections were completed during the dry season, and surface water salinities at the three sites ranged from 35-37 ppt. The salinity at Bundaberg during a wet season visit was 29, Townsville 12 and Cairns 29 ppt. The percentage of the pile surface area covered by barnacles near the mid-tide region on the downstream face of the piles was estimated. At first, the estimate was attempted by counting barnacles within a 200 mm square grid, however, it was soon realised that results depended greatly on exactly where the grid was placed on the pile surface. Therefore, estimation over the whole downstream face of the mid-tide area was made subjectively, and seemed more accurate.

Sampling barnacles for copper, chromium and arsenic at Townsville

Barnacles at Townsville were collected from five or six piles of each treatment within the inspection time available, and four untreated *S. glomulifera* piles. Two days before inspection, the Townsville Port Authority scraped each pile in the tidal zone, except for the downstream face. During inspection and after estimating percentage barnacle growth on this downstream face, all remaining barnacles were scraped from the piles. Barnacles from the mid-tide region of the downstream face were collected and placed into 28 ml McCartney vials containing 70% ethanol. An average of 6 barnacles of diameter 11-16 mm, 10 barnacles 4-10 mm and 13 barnacles 2-3 mm were collected from each pile. Since all barnacles were removed during each inspection, barnacles collected at the four year inspection could not be more than two years old. Most barnacles collected were *Balanus* species (Poore, pers. comm.).

In the laboratory, all soft tissue was removed from the barnacle shells under a dissecting microscope, using stainless steel forceps. Bryan *et al.* (1985) found no evidence that dissecting with stainless steel instruments caused metal contamination. A blank was created, where stainless steel forceps were rubbed together in 70% ethanol, the sample oven dried and 10% HCl added to the vial, but insignificant metal was obtained. During dissection, care was taken not to include any shell or treated wood fibres adhering to the basal plate of the barnacles. The soft tissue was placed on a tared watchglass, weighed, and oven dried overnight at 105°C to determine dry mass. Mean wet mass of the tissue samples from each pile was 1410 mg (standard deviation 490), and mean dry mass was 204 mg (sd 79).

Cu/B/F also contained chelated copper in the form of copper diglycinate. Copper diglycinate is a charge-neutral complex which we knew to be an effective fungicide (2). The structure assigned to copper diglycinate is shown in Figure 1 (3).

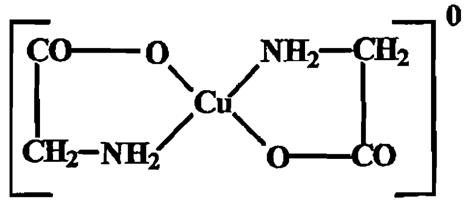

FIGURE 1 Copper diglycinate

We tested the experimental rods and the Polesaver™ controls in a 12 month stub diffusion trial. The stubs were stacked (out of soil contact) in the Accelerated Field Simulator (AFS) at Clayton. Green *E. sieberi* L.Johnson (Silvertop ash) regrowth was used as the diffusion substrate and samples were removed at 3 monthly intervals for inspection/analysis.

MATERIALS AND METHODS

Preparation of experimental rods

Both the B/F and the Cu/B/F rods were made using a propylene glycol borate ester bonding agent, formed by the reaction between propylene glycol and boric oxide according to :-

$$3(C_2H_5OHCH_2OH) + 2B_2O_3 \Leftrightarrow B_2O_6C_9H_{21} + 2H_3BO_3$$

It was found that the reaction mixture polymerised to a plastic mass if the reaction was carried out at about 115°C. On cooling to ambient temperature, a glassy solid was formed.

The B/F rods were prepared by reacting propylene glycol and boric oxide for 45 minutes at 115°C and then mixing in sufficient sodium fluoborate ($NaBF_4$) to give the composition shown in Table 1. About 5% m/m guanidine carbonate ($[(NH_2)_2C{:}NH]_2 \bullet H_2CO_3$) was included as a buffer.

TABLE 1 Properties of Polesaver™ and experimental preservative rods.

Property	Polesaver™ rods	Experimental rods B/F	Experimental rods Cu/B/F
Active elements (% m/m)	12.4 B 11.0 F	16.1 B 18.7 F	12.9 B 14.9 F 6.2 Cu
Total active elements (% m/m)	23.4	34.8	34.0
Rod density (g/mL)	1.5	1.64	1.69
Solubility (g/L)	95 (at 20°C)	145.3 (at 25°C)	130.0 (at 25°C)
Solution pH	7.6 (sat. soln)	5.5 (sat. soln)	4.0 (sat. soln.)

The plastic mass from the reaction vessel was pressed into 15 mm diameter holes drilled into a 50 mm thick slab of teflon. The mixture solidified after a few minutes to yield white, glassy, semi-translucent rods.

The Cu/B/F rods were made in a similar manner. The copper diglycinate had been previously prepared by reacting stoichiometric quantities of glycine and copper hydroxide in boiling aqueous solution and then evaporating the solution at 60°C to give a dry, powdery solid. The copper diglycinate powder was mixed into the hot propylene glycol ester, together with sodium fluoborate, to give a dark blue paste, which solidified to rods when cooled to below 60°C in the teflon mould.

Both sets of experimental rods contained about 45% more active elements (m/m) than the Polesaver controls (Table 1). The Cu/B/F rods included the equivalent of 6.2% elemental copper on a m/m basis.

Slab diffusion bioassay

The fungitoxicity and diffusibility of the experimental rod formulations and the copper diglycinate chelate were tested by the slab diffusion method originally described by Da Costa and Greaves (4).

In their method, the candidate formulation is incorporated into a strip of open-celled sponge in the bottom of a Petri dish. A water saturated wooden slab, measuring 50 x 50 x 6 mm with the edges sealed by dipping in petroleum jelly and paraffin wax, is placed on top of the sponge. Diffusion of the preservative through the slab is assessed by placing a strip of inoculated agar on top of the slab, at right angles to the grain direction. Inhibition of fungal growth on the strip of inoculated medium will occur if the preservative diffuses through the slab and attains an effective concentration of toxicant on the surface.

Slabs of heartwood and/or sapwood were cut from three different pole timbers: *E. drepanophylla* F. Muell, ex Benth. (Grey ironbark); *E. maculata* Hook.(Spotted gum); and *E. obliqua* L'Herit. (Messmate). The heartwoods of these timbers were representative of durability classes 1, 2 and 3 respectively (6). The oven-dry basic densities ranged from about 870 kg/m^3 (Grey ironbark) to about 540 kg/m^3 (Messmate).

Six replicate slabs were used to test each formulation. Untreated controls were also included for reference. All slabs (including the untreated controls) were incubated at 28°C and 85% RH and rated for fungal activity after 7, 14, 21 and 28 days.

After completion of the diffusion tests, the top surfaces of the slabs were sprayed with indicators (prepared according to AS 1605 - 1974 (7)) to detect the presence of the diffusible elements.

Stub diffusion trial

Fifty 500 mm long stubs were cut from freshly harvested Silvertop ash (*E. sieberi*) regrowth logs taken from the Boola Boola State Forest near Erica, Victoria. The stub diameters ranged from about 135 mm to 265 mm (under bark). The fifty stubs were cut from about a dozen different logs. Care was taken to ensure that each stub had intact, tightly adhering bark and contained no gross defects such as branch stubs or large kino pockets. Each stub was individually packed in a plastic bag immediately after cutting to minimise moisture loss during transport and storage.

In the laboratory, the stubs were fitted with tensioned steel straps 18 mm wide by

0.7 mm thick placed about 20-30 mm from the cut ends. The steel straps served to minimise end checking and splitting of the stubs during the subsequent diffusion trial. Since it was important for the stubs to stay moist during the trial period in order to permit diffusion of the active elements, the cut ends of the stubs were then painted with two coats of epoxy enamel to further reduce evaporative losses.

Of the 50 stubs originally collected, 36 were selected for the actual diffusion tests. A 16 mm diameter hole was drilled axially to a depth of 250 mm in each stub to accommodate the diffusible rods. The drilled stubs were sorted on the basis of diameter into four groups of nine. In each group of nine, three stubs were treated with the Polesaver controls. A Polesaver™ rod was tamped to the bottom of the 16 mm diameter hole in each stub and the hole then sealed with a screw-in plastic plug. A further three stubs in each group were similarly treated with the experimental B/F rods (two rods per hole) and the remainder with the experimental Cu/B/F rods (again two rods per hole, see Table 5). The treated stubs were then vertically stacked in the AFS, to be maintained at 28°C and 85% RH for the duration of the test.

The treated stubs were removed in groups of nine at three monthly intervals, with the smallest diameter stubs being removed first.

At sampling, the plastic screwplug was removed from each log and the log split along the drill hole with a steel wedge. The remains of the preservative rods were carefully removed for later weighing and the fractured surfaces of the split logs then planed smooth with a power plane.

The planed surfaces of the logs were sprayed with indicators to detect the presence of the diffusible elements. After application of the indicators, grid lines were drawn on the planed log surfaces. One centrally positioned axial line was drawn and then three radial lines at right angles to the axial line. Measuring from the drilled (top) end of the log, the radial lines were spaced 125 mm apart, with the second of the lines being drawn immediately below the base of the drill hole.

The extent of diffusion of the active elements, as shown by the indicators, was measured at the top surface of the log (if applicable) and then at the points of intersection of the indicated colours with the grid lines and also at the base of the log (if the element had diffused that far). In that way, the extent of diffusion of the active elements was comparably recorded for each log.

When only two active elements were present, one element was measured on one face of the split log and the other on the opposing face. With three elements, one of the previously tested faces was planed clean again (the indicator penetrated the wood to less than one millimetre depth) and the cleaned face then tested for the third element.

Analytical samples

During the last round of sampling (after 12 months), transverse sections were cut from the split logs for analysis of the diffusing elements.

The sections for analysis were 25 mm thick and were cut from the portion 25-50 mm below the central drill hole. One section was cut from each half of the split log. The two sections were then fitted together to form a disc and a 50 mm square portion chiselled out from the centre of the disc. This formed the analytical sample.

The analytical sample was further chipped with the chisel, the chips air dried for two days at about 32°C and then Wiley milled to pass a 2 mm hole diameter screen.

The elemental analyses were performed by Mr Michael Kennedy, QDPI Forest Service, at their Indooroopilly laboratory. An Inductively Coupled Plasma (ICP) analyser was used to determine boron and copper concentrations whilst the fluorine content was measured by ultra-violet absorption.

RESULTS AND DISCUSSION

Slab diffusion bioassay

The results of the slab diffusion bioassays of the two experimental rod formulations and the copper diglycinate chelate are summarised in Table 2.

TABLE 2 Slab diffusion bioassay of experimental B/F and Cu/B/F rod formulations and copper diglycinate chelate.

Substrate	Test preservative	Rating after diffusion period (days)*			
		7	14	21	28
Grey ironbark (sapwood)	B/F	0	0	0	0
	Cu/B/F	0	0	0	0
	Untreated control	2.8	3.0	3.0	2.7
Grey ironbark (heartwood)	B/F	0	0	0	0
	Cu/B/F	0	0	0	0
	Copper diglycinate only	1.5	2.2	0.8	0
	Untreated control	3.0	3.0	3.0	2.7
Messmate (sapwood)	B/F	0	0	0	0
	Cu/B/F	0	0	0	0
	Untreated control	2.5	3.0	3.0	3.0
Messmate (heartwood)	B/F	0	0	0	0
	Cu/B/F	0	0	0	0
	Untreated control	3.0	3.0	2.7	2.5
Spotted gum (heartwood)	Copper diglycinate only	1.7	2.3	1.3	0.2
	Untreated control	2.3	2.8	3.0	3.0

* *Rating:* 0- no evidence of fungal growth; 1- slight mycelial development; 2- moderate fungal growth; 3- vigorous fungal growth.

We generally assess the efficacy of a diffusible preservative after 28 days of testing. A score of 0 is taken as "Very effective", whilst a score of <1 is regarded as "Effective".

The two experimental rod formulations were rated as "Very effective", with zero scores on all five test substrates. Copper diglycinate scored zero with the Grey ironbark heartwood slabs and 0.2 with the Spotted gum heartwood slabs, showing it to be an effective diffusible fungicide in its own right.

Spraying the top surfaces of the diffusion slabs with elemental indicators at the end of the 28 day diffusion period showed a strong indication for boron and a fair to strong indication for fluorine for the B/F rod formulation (Table 3).

TABLE 3 Elemental indication of top surfaces of diffusion slabs after 28 diffusion period.

Substrate	Rod formulation	Elemental indication*		
		Boron	Fluorine	Copper
Grey ironbark (sapwood)	B/F	xxx	xxx	-
	Cu/B/F	xxx	xxx	xxx
Grey ironbark (heartwood)	B/F	xxx	xx	-
	Cu/B/F	xxx	xx	xxx
Messmate (sapwood)	B/F	xxx	xxx	-
	Cu/B/F	xxx	xxx	xxx
Messmate (heartwood)	B/F	xxx	xx	-
	Cu/B/F	xxx	xx	xxx

* **x**- slight indication; **xx**- fair indication; **xxx**- strong indication

The copper in the Cu/B/F rod formulation diffused freely in the presence of the other two biocidal elements, as shown by the strong indication for copper on both the heartwood and sapwood slab samples.

Stub diffusion trials - characteristics of test logs

The mean initial moisture content of the stub diffusion logs was 106% at the beginning of the trial. As might be expected, the stubs dried out to some extent during the trial period. The greatest loss of moisture occurred during the first three months. Thereafter, the moisture content remained relatively constant at about 50-60% (Table 4). None of the logs dried below fibre saturation point (about 30%) and hence the active elements were free to diffuse throughout the trial period.

TABLE 4 Stub diffusion trials - characteristics of test logs.
Test material - Silvertop ash (E. sieberi) regrowth cut into 500 mm lengths
Initial moisture content - 106.1%

Stub Nos.	Mean diameter * (mm) [Standard Deviation]	Sampling interval (months)	Mean moisture content (%) [Standard Deviation]	Mean basic density (kg/m³) [Standard Deviation]
1-9	149 [7.4]	3	57.4 [6.4]	605 [25.6]
10-18	165 [9.6]	6	51.3 [7.6]	592 [24.8]
19-27	223 [13.3]	9	64.4 [17.5]	558 [45.0]
28-36	234 [12.8]	12	53.6 [13.0]	621 [53.1]

* Average of minor and major axes

The oven-dry basic densities of the diffusion stubs were typical of this type of material and in line with a more extensive sampling of Silvertop ash regrowth previously undertaken in East Gippsland (5). There was no significant correlation between basic density and mean stub diameter. In practical terms, this meant that the basic density of the stubs did not impart an overall bias to the measured extent of diffusion. The smaller diameter stubs (which were sampled first) had much the same basic density as the larger diameter stubs, which were sampled last.

Weight of active elements in the diffusion stubs

The average weights of the B/F and Cu/B/F rods were 14.0 g and 14.4 g respectively. At two rods per stub, the total weight per stub of the experimental formulations was thus higher than the 23.0 g for the control Polesaver™ rods. The amounts of active elements per stub for each of the three treatments are summarised in Table 5.

TABLE 5 Amounts of active elements per diffusion stub with test rods.

Rods	Active elements/stub (g)			Total
	B	F	Cu	(g)
Polesaver™ (1 rod, 14 mm diam.x 125 mm long, 19.2 mL)	2.85	2.53	-	5.38
B/F (2 rods, 15 mm diam. x 50 mm long, 17.7 mL)	4.51	5.24	-	9.75
Cu/B/F (2 rods, 15 mm diam. x 50 mm long, 17.7 mL)	3.72	4.29	1.79	9.80

The higher density and higher active element concentrations in the experimental B/F and Cu/B/F rod formulations (see Table 1) gave an increased loading of biocidal components per unit volume of rod compared to Polesaver™.

Diffusion of active elements in test stubs

The rate of indicated longitudinal diffusion was such that all of the active elements in all three rod samples had diffused 250 mm from the base of the drill hole to the base of the diffusion stubs within 9 months (Figure 2).

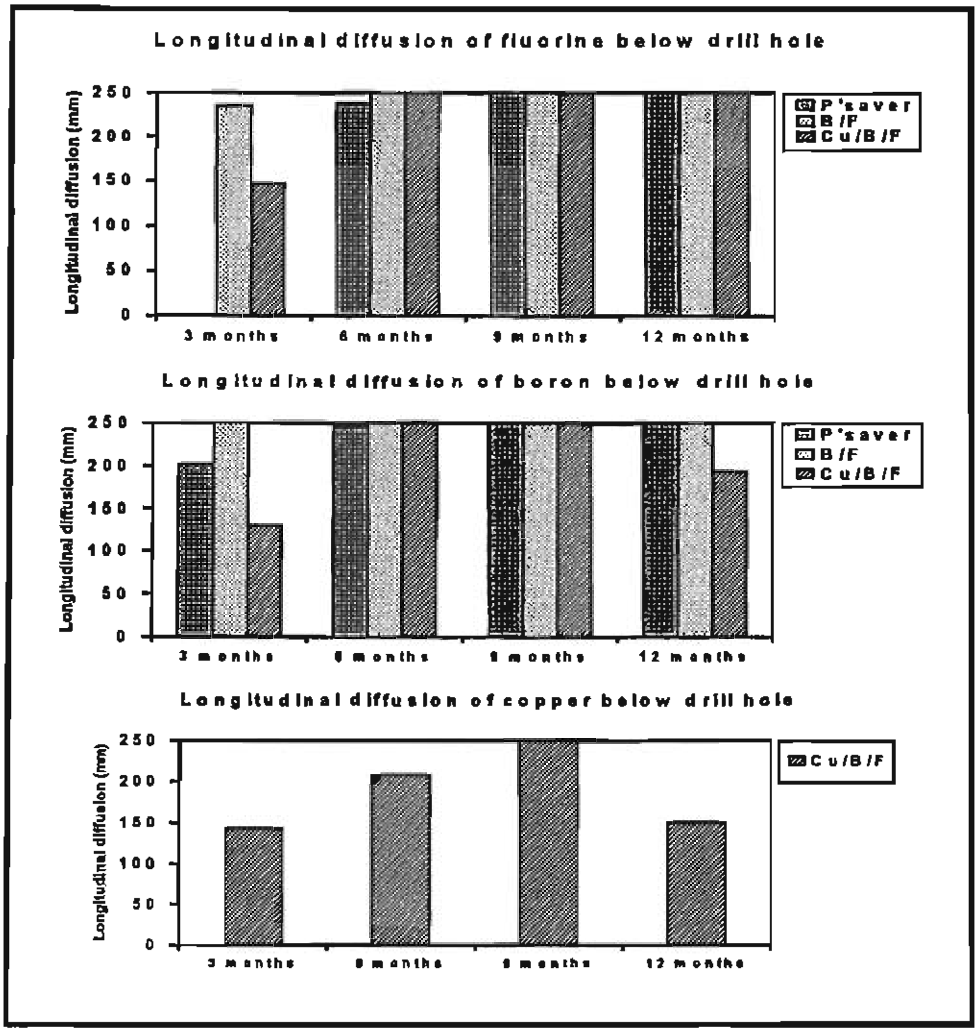

FIGURE 2 Indicated longitudinal diffusion of active elements in diffusion trial

The longitudinal diffusion of copper from the Cu/B/F rods was apparently not inhibited by the presence of borate and fluoride anions in the formulation. The seemingly anomalous result of a lesser longitudinal diffusion of boron and copper at 12 months observed with the Cu/B/F rods was caused by twisted grain and kino pockets within the centre of the larger diameter stubs, defects which were not obvious until the stubs were split for inspection.

The extent of indicated radial diffusion of the elements, as measured immediately below the drill hole, was less affected by defects within the stubs and generally progressed steadily over the 12 month test period (Figure 3).

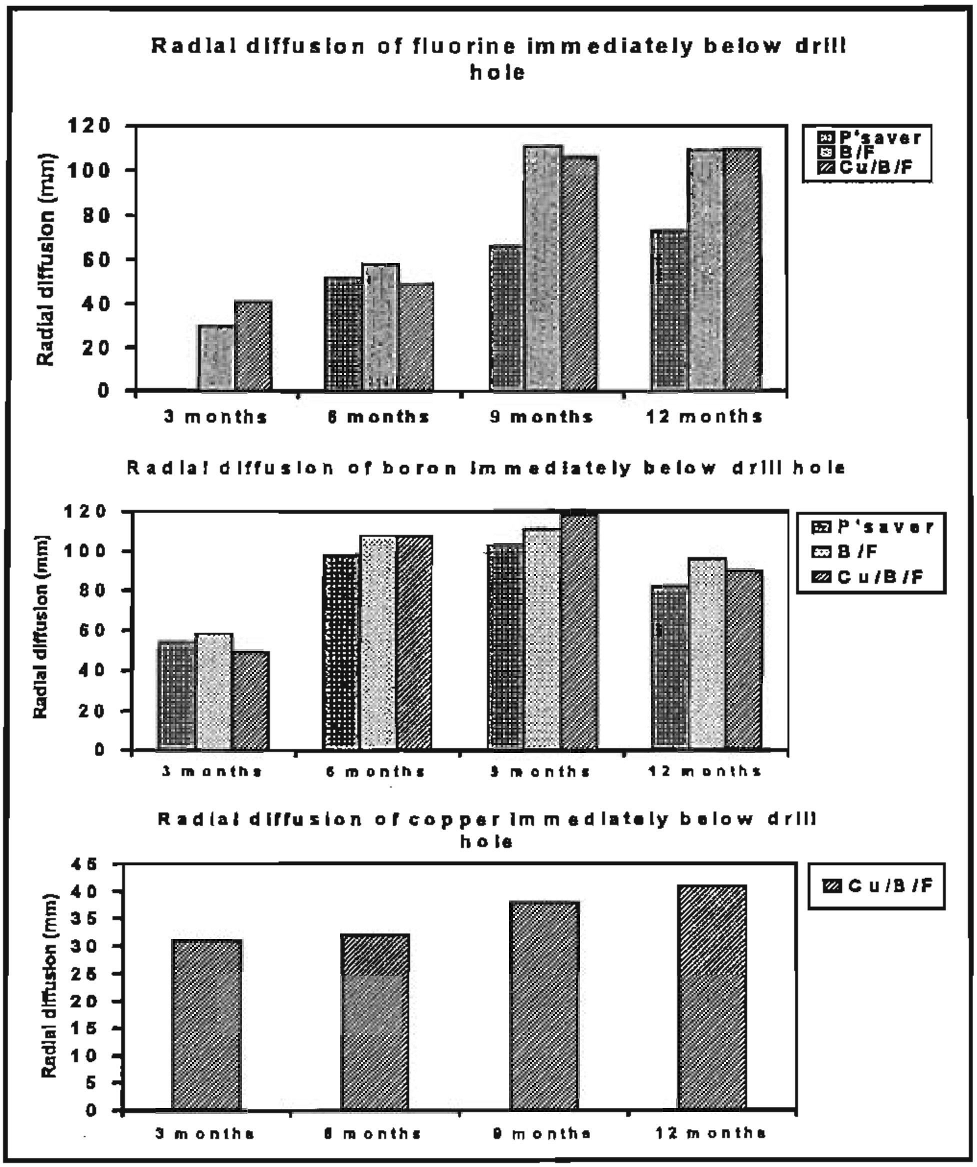

FIGURE 3 Indicated radial diffusion of active elements immediately below drill hole in stub diffusion trial

The boron diffused faster than the fluorine, which in turn diffused faster than the copper. The two sets of experimental rods gave a slightly better penetration of boron and fluorine than the Polesaver™ controls, probably due to the higher amount of these elements in the initial formulations (Table 5).

The average indicated extent of radial diffusion of copper, as measured at the top and base of the stubs and three intermediate positions, steadily progressed throughout the stubs during the first 9 months of the trial (Figure 4). There were some anomalies with the 12 monthly measurements because of the previously noted twisted grain and kino pockets, but even then there was extensive diffusion of copper in the upper half of the stubs, adjacent to the drill holes.

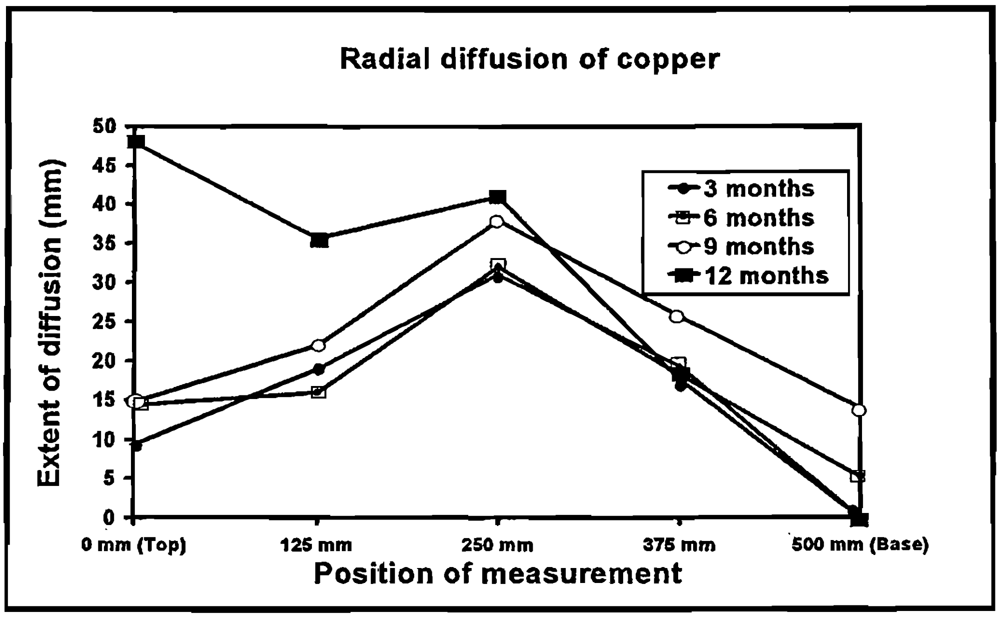

FIGURE 4 Average radial diffusion of copper during 12 month trial period

Extent of dissolution of preservative rods

As might be anticipated, the rods dissolved faster during the first half of the trial than during the second half (Table 6). The Polesaver™ controls dissolved to a greater extent than the two experimental formulations. However, in all three instances, there was sufficient of the rods left in the stubs to provide residual protection beyond the twelve month test period.

TABLE 6 Extent of dissolution of the preservative rods

Rod	Amount dissolved (%)		
	after 6 months	after 9 months	after 12 months
Polesaver™	68	79	86
B/F	55	69	63
Cu/B/F	60	68	68

Elemental analysis of the 12 month diffusion samples

The results of the elemental analyses on the sample blocks taken from the stubs after 12 months of diffusion are summarised in Table 7.

TABLE 7 Analysis of 12 month diffusion samples

Samples :- 50 x 50 x 25 mm blocks taken from the section 20-25 mm below the drill hole in the centre of the stubs.

Rod	Equivalent loadings (% m/m)		
	B. [as H_3BO_3]	F [as NaF]	as Cu
Polesaver™	0.144 [0.82]	0.41 [0.90]	-
B/F	0.101 [0.58]	0.59 [1.30]	-
Cu/B/F	0.079 [0.45]	0.40 [0.88]	0.057

The results confirmed that copper was the least diffusible of the three elements. The average amount of copper in the sample blocks was 10.6% m/m of the active elements, compared to 18.1% m/m in the original Cu/B/F rods (Table 1). This may be attributed to the relatively low solubility of the copper diglycinate (10 g/L at 21°C) and the comparatively large size of the copper diglycinate chelate complex, which would have hampered the rate of diffusion of the complex through the wood substance (3).

CONCLUSIONS

The results have shown that a neutral-charge copper chelate can be incorporated into preservative formulations containing boron and fluorine as active elements. The copper continued to diffuse in the presence of these elements for the duration of the 12 month test period, without forming insoluble copper fluorides or borates. This ability to include diffusible copper (and other fungitoxic metals) into remedial treatment formulations is something new to the industry and points the way to a whole new class of wood preservative systems.

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MEASURING CHANGES IN WOOD CAUSED BY ALKALI TREATMENT OR FUNGAL DECAY BY USING NEAR-INFRARED SPECTROSCOPY

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ABSTRACT

The paper describes the possible application of near-infrared (NIR) spectroscopy to studies of the chemistry of wood decay. It shows similarities between changes in the NIR spectra of wood resulting from alkali/holocellulose treatments and those resulting from decay. Results obtained for the chemistry of woods from NIR spectral studies are described and parallels with the chemistry of decayed wood drawn. Possibilities exist for NIR spectra to be obtained from the interior of wood in service.

INTRODUCTION

The chemistry of wood decay is a subject of considerable scientific and economic importance (Zabel and Morrell,1992). New developments in analytical instrumentation and computing have made feasible extensive studies of the variability of the chemical components of woods including such properties as kraft pulp yield (Schimleck *et al.*, 1996). These studies, hitherto might have been thought to be prohibitively time-consuming and expensive. This paper explores the prospect that these developments might be applied similarly to studies of the chemistry of wood decay. They involve the use of near-infrared (NIR) spectroscopy and require only small samples which might be easily obtained from samples in service. The instruments are robust and could be portable.

The primary chemical components of wood are cellulose, non-cellulosic polysaccharides, lignin and extractives. That these can be analysed by NIR spectroscopy has been demonstrated by a number of authors (Birkett and Gambino,1988; Garbutt *et al.*,1992; Wright *et al.*,1990; Schultz and Burns,1990; Olsson *et al.*,1995). The decay fungi attack these components at different rates and to different degrees. Changes in the wood components resulting from fungal attack ought then be able to be assessed by measuring the changes in the NIR spectra of the decayed and decaying woods.

EXPERIMENTAL

The wood meal used to obtain the NIR spectra was produced by milling according to Australian Standard AS1301 002s-91. The sample of cellulose was a commercial sample - Avicel^{R} PH101. The sample of xylan was obtained as the residue from the extraction under nitrogen of *Eucalyptus regnans* holocellulose with 24% potassium hydroxide. The origins of the eucalypt milled wood lignin and hot water extractives samples have been given (Turner *et al.;*1983, Michell,1994)). The alkali and holocellulose treatments were as outlined (Harrington *et al.*,1964).

The decayed wood sample was *E.regnans* from a severely decayed fence rail in outdoor exposure in Melbourne. The blocks were *P. radiata* sapwood treated with various loadings of copper sulfate and exposed to several strains of the brown-rot fungus *Antrodia vaillanti* with the weight loss extending to *ca.* 75 percent.

The NIR spectra were measured in diffuse reflection from samples contained in a rotating sample cup in a NIR Systems Inc Model 5000 scanning spectrophotometer. The reference was a ceramic standard. The spectra were collected at 2 nm intervals over the range 1100-2500 nm. A total of 50 scans was accumulated for each of duplicate samples and their scans were averaged. The scan time is 35 s.. The spectra were converted to the second derivative mode using the instrument's software with a segment of 10 nm and a gap of 20 nm. Partial least squares (PLS) regression models and values of correlation coefficients for bands in the NIR spectra were obtained by using the instrument's software.

RESULTS AND DISCUSSION

The NIR spectra of *E. globulus* wood, and of its components cellulose, xylan, lignin and extractives are shown in Figure 1.

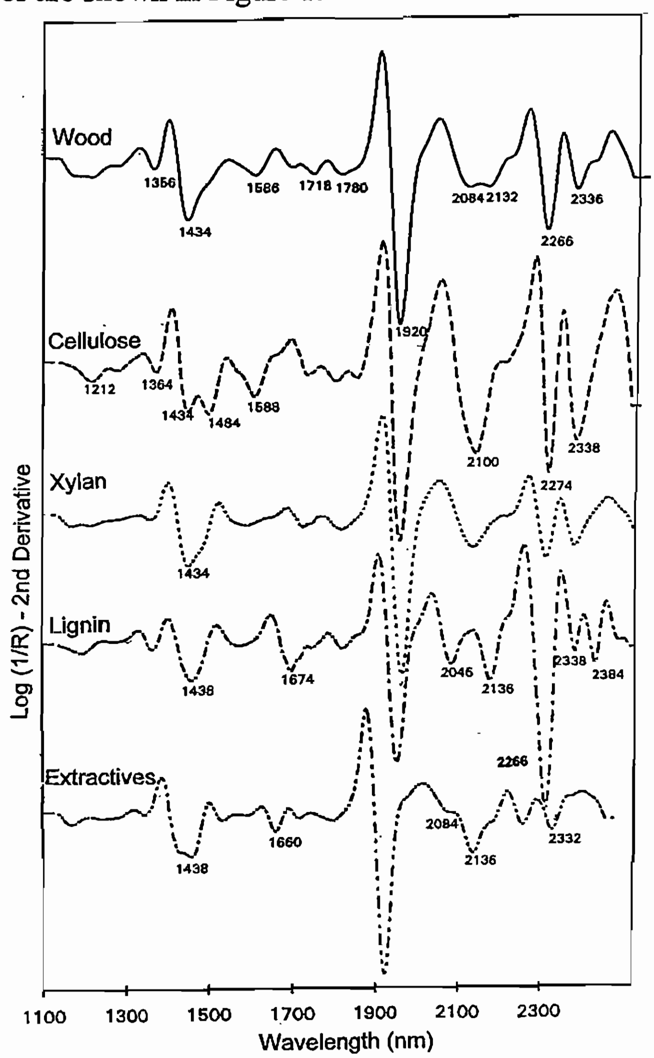
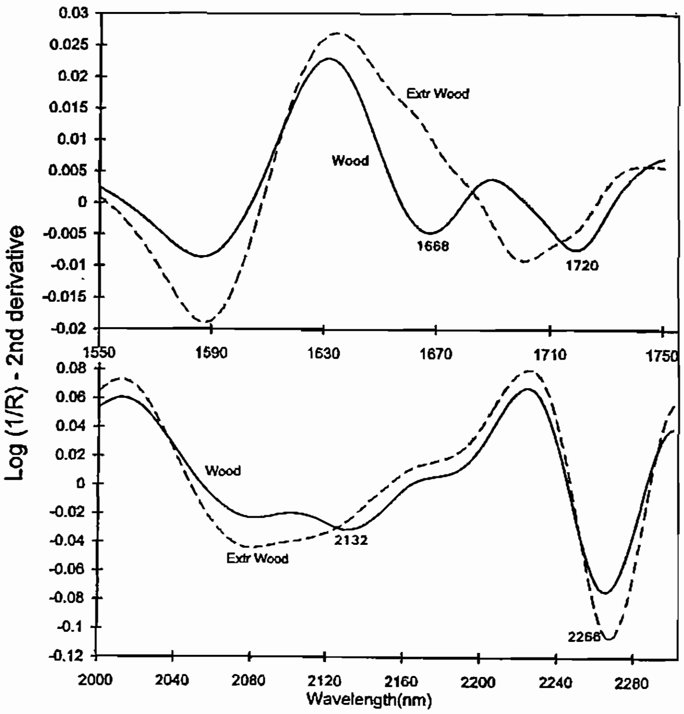


Figure 1. NIR spectra of *E. globulus* sapwood and of its components, cellulose, xylan, lignin and extractives.

The spectra are shown in the second derivative form with the peaks pointing downwards. The differences in the spectra of the components are evident. Two of the most prominent bands which are present in the spectra of all the components, are those near 1434 and 1920 nm, which arise from moisture in the samples. Thus moisture in wood can be measured by NIR spectroscopy.

Another method for showing the contributions of the wood components to the overall spectrum is to examine the spectra of wood samples which have been treated with chemicals to remove preferentially some of the components. In Figure 2 are compared the NIR spectra of wood and of wood which has been extracted with dilute alkali.



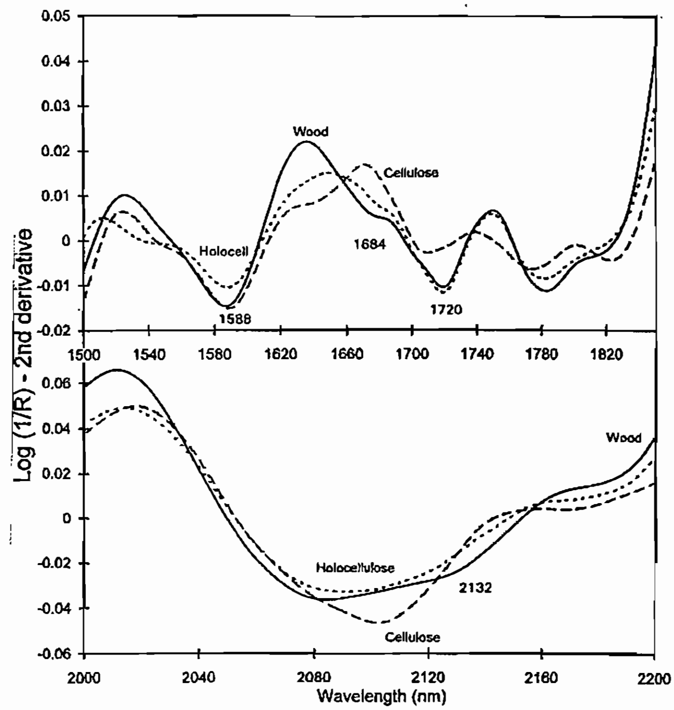


Figure 2. NIR spectra of *E. globulus* wood before and after extraction with weak alkali

Figure 3. NIR spectra of *E.globulus* wood, holocellulose and cellulose

In Figure 2 two regions of the spectra are shown namely, 1550-1750 nm and 2000-2280 nm. The effect of the alkali treatment is to weaken severely bands at 1668, 1720 and 2132 nm. The bands at 1668 and 2132 nm are known to arise, in part, from a C_{ar}-H vibration of a type found in polyphenolic extractives and lignin (Michell and Schimleck, 1996).

Figure 3 compares the spectra of wood, holocellulose (wood minus lignin) and cellulose (wood minus lignin minus non-cellulosic polysaccharides). A number of differences are evident with the changes in the regions of 1684 and 2132 nm discussed for the spectra of the alkali-extracted wood prominent.

The spectra of a sound and decayed wood sample are shown in Figs 4-6.

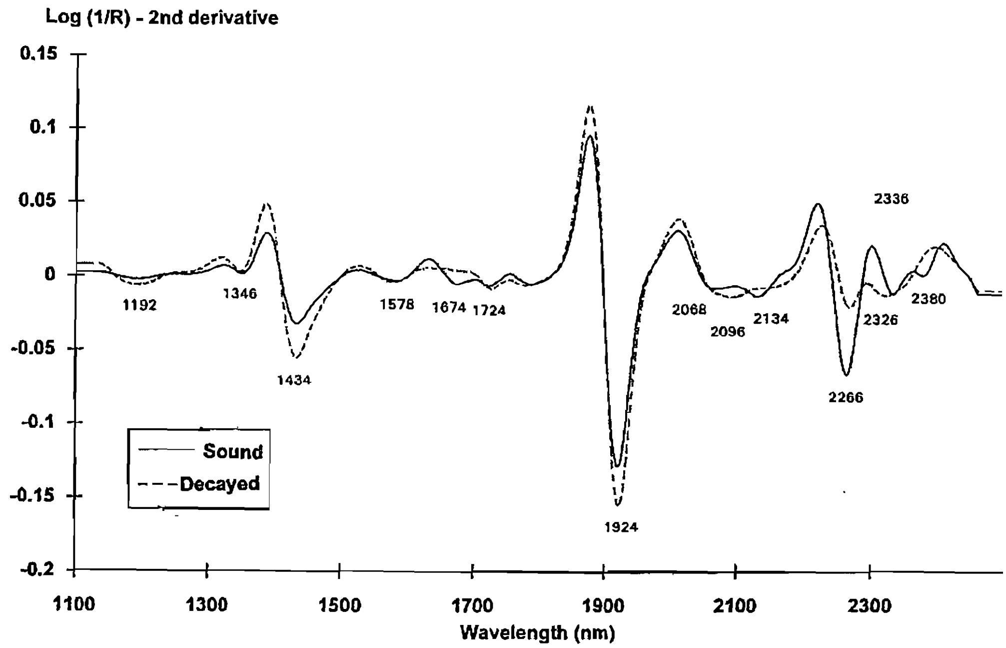


Figure 4. NIR spectra (1100- 2500 nm) of sound and decayed *E.regnans* wood.

Many differences are apparent in the spectra including the moisture sensitive bands near 1434 and 1920 nm. These are more easily seen in the expanded spectra of particular regions. Figure 5 shows expanded spectra for the region 1500-1800 nm.

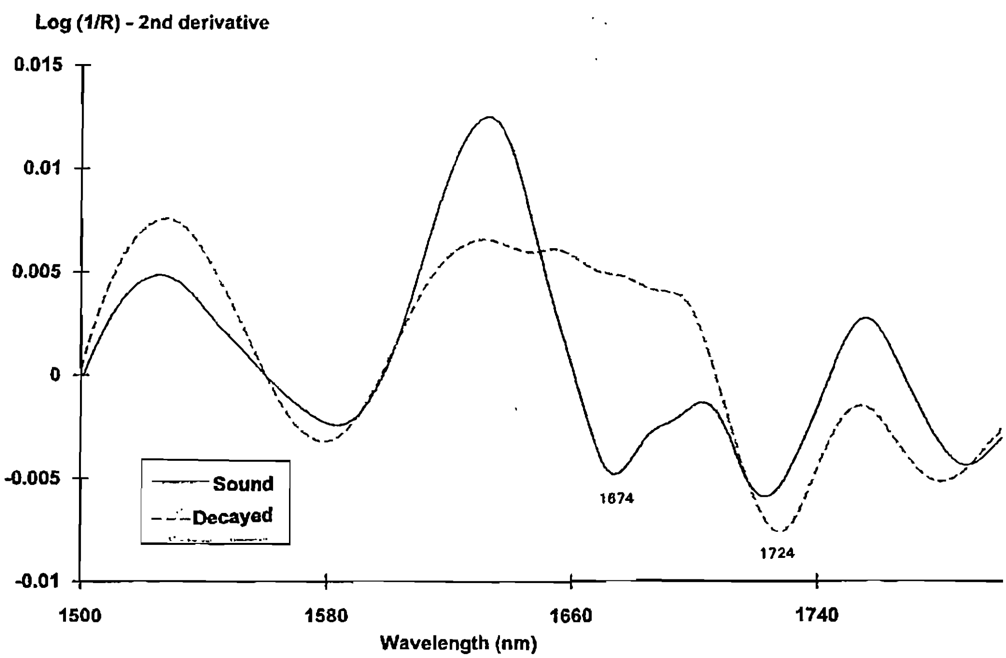


Figure 5. Expanded NIR spectrum (1500 - 1800 nm) of sound and decayed *E. regnans* wood.

The most obvious difference in this spectrum is the loss of intensity of the band near 1674 nm in the spectrum of the decayed relative to that of the sound wood. This band must have very similar origins to those discussed previously in this region in connection with alkali-extracted woods.

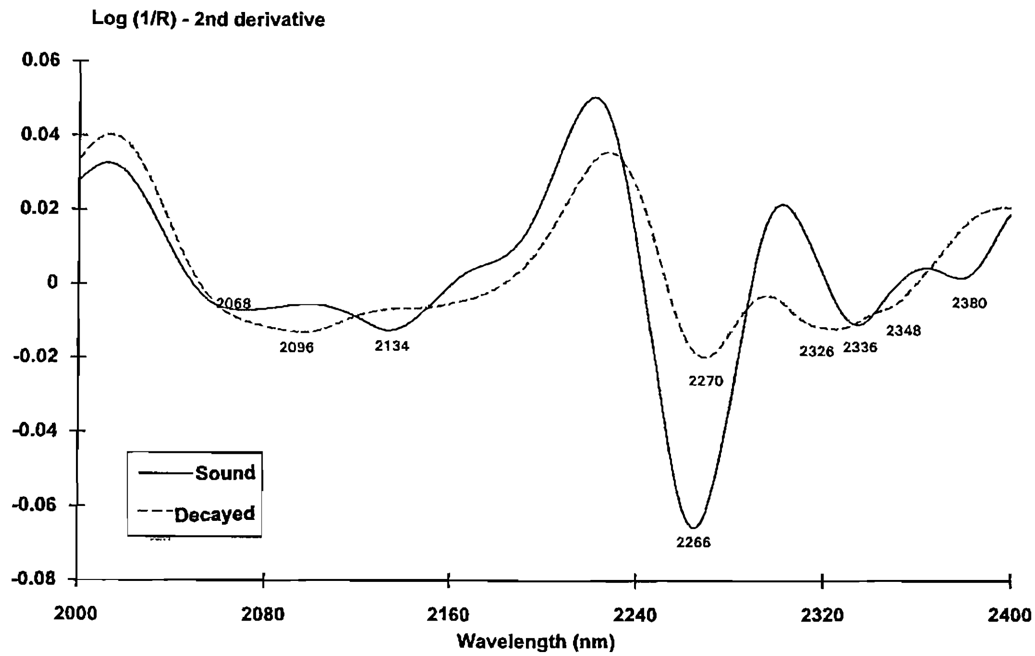


Figure 6. Expanded NIR spectra (2000-2400 nm) of sound and decayed *E. regnans* wood.

In this spectrum the most prominent loss of intensity of a band in the decayed wood spectrum relative to the sound wood is that of the band at 2266 nm. Figure 1 shows a very strong band for lignin at this wavelength and the weakening of this band in the decayed wood is strong evidence of delignification. There are also changes in intensity in the band at 2134 nm similar to those observed previously in the alkali treated wood and related to lignin and polyphenols.

The NIR spectrometer as described here records 700 data points. Models based on these points have been related to the amounts of the woody chemical components such as cellulose, non-cellulose polysaccharides, lignin, extractives, and acetyl contents so that these can now be predicted in unknown woods by simply measuring the NIR spectrum (Schimleck *et al.*, 1996). As we have shown above, changes in wood chemistry brought about by decay organisms appear to be very similar to those resulting from chemical treatments and thus NIR spectra should provide an excellent means of monitoring the chemistry of wood decay.

We did not have any chemically analysed samples to test this but were able to obtain 124 small *P. radiata* sapwood blocks which had been part of a test involving copper sulfate pentahydrate and various strains of the brown-rot fungus *Antrodia vaillanti.* The losses in weight varied from near zero to *ca.*75 percent. The NIR spectra of 93 of the samples were used to obtain a PLS regression model. A single factor model had a correlation coefficient of 0.74. The model and the NIR spectra of the remaining 31 samples were then used to predict the weights of these samples and the result is shown in Figure 7. The data are rather sparse at the high decay end and the model predicts weights which are too high. Overall, the standard deviation of residuals was 0.25.

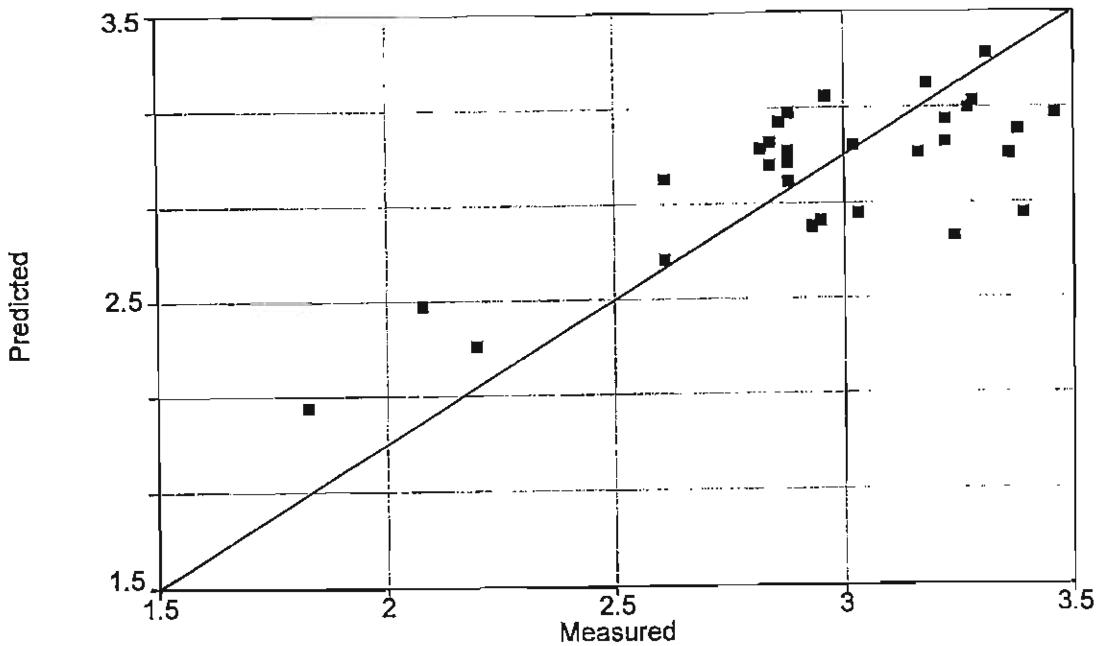


Figure 7. Predicted vs measured weights for validation samples.

Better predictions would be expected for precise chemical entities than for a sum such as the weights.

There are also further opportunities for NIR spectroscopy to be useful. The samples we have used in the work described above have been in the form of wood meal. However, other sampling modes are possible with the one of particular interest being a hand-held fibre-optic diffuse reflectance probe (Figure 8).

Figure 8. Fibre optic NIR diffuse reflectance probe as offered by a commercial supplier.

Such probes are now as fine as 4-6 mm in diameter and do not have to be pressed against a flat surface but can be held a few millimetres off the surface and still give good spectra. We have obtained spectra from dressed wood surfaces with borrowed probes of this kind. The narrow diameter and relative small size of the attached electronics makes possible the design of a portable tester with a probe able to be placed into small holes drilled into wood in service. As we have shown above the potential information about the chemical state of the reflecting surface is quite sophisticated and if the necessary calibrations have been obtained might give useful information about the nature and progress of the wood decay.

CONCLUSIONS

NIR spectroscopy can be used to monitor changes in wood chemistry resulting from decay. Further work is required to determine how early in the decay process these changes can be detected and how well different types of decay can be differentiated by this means.

It also seems likely that the NIR spectroscopic methods as developed might be used for detecting decay in wood in service by placing fibre optic reflectance probes in narrow drilled holes in the wood.

ACKNOWLEDGMENTS

The authors thank Ms O. Collett for providing samples of decayed *P. radiata* wood blocks and their weights.

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25th FOREST PRODUCTS RESEARCH CONFERENCE
NOVEMBER 1996

International collaborative laboratory comparison of two wood preservatives against subterranean termites: Third update.

J.R.J. French[1]

in cooperation with

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Paper prepared for the 25th Forest Products Research Conference, Melbourne, 18-21 November, 1996

Footnote: This is a modified version of the paper prepared for the 27th International Research Group on Wood Preservation annual meeting at Guadeloupe, France, in May 1996.

International collaborative laboratory comparison of two wood preservatives against subterranean termites: Third update.

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ABSTRACT

This comparative laboratory evaluation of two wood preservatives, copper-chrome-arsenic (CCA) and copper naphthenate (Cu-Na) against the subterranean termites used as test termites in Australia, France, Japan, Thailand, United Kingdom and the USA. Solutions of these two wood preservatives were prepared and impregnated into *Pinus radiata* wood blocks to obtain loadings of 0.0, 0.5, 1.0, 2.0 and 4.0 kg/m^3 respectively. All preservative treatments were carried out at the Division of Forestry and Forest Products in Melbourne.

This paper reports the results of the amount of wood consumed and the mean mass loss (%) on both treated and untreated wood blocks by the termites in the various laboratory bioassays. All bioassays indicated that CCA and Cu-Na effectively protects wood against termites at the loading selected. At the workshop of participants at the 27th annual meeting of IRG in Guadeloupe the results of this study were discussed and recommendations were made for future continuation of this study.

Keywords: collaborative test; subterranean termites; comparative laboratory bioassay; copper-chrome-arsenic; copper naphthenate.

INTRODUCTION

At the 24th annual meeting of IRG in Orlando, USA, in May 1993, it was agreed to initiate an international subterranean termite laboratory bioassay to compare the various preferred termite protocols used by the IRG termitologists present at the termite workshop. The author (JRJF) was nominated by those members present at the working party to co-ordinate the evaluation. Two preservatives, copper-chrome-arsenic (CCA) and copper naphthenate (Cu-Na) were to be assessed against the subterranean termites selected and routinely tested by the various participating members in a no-choice bioassay situation .

All preservative treatments were carried out at the Division of Forestry and Forest Products in Melbourne. The treated specimens were dispatched to the participating researchers from Australia, France, Germany, Japan, Thailand, United Kingdom and the United States of America. Participants subjected these specimens to attack by their test termite species, and have now returned the specimens to Melbourne.

This paper reports the amount of wood consumed and mean mass loss (%) on both treated and untreated wood blocks by the termites in the various laboratory bioassays.

MATERIALS AND METHODS

Timber: All the wood specimens were prepared from radiata pine sapwood (*Pinus radiata* D.Don) and cut into dimensional sizes according to the individual termitologist's protocol (see French 1995).

Preservative retentions: Wood specimens were treated with CCA or Cu-Na to achieve the retentions as follows:- 0.0, 0.5, 1.0, 2.0 and 4.0 kg/m^3.

Treatment: A full cell treatment schedule was used to treat the blocks. It is considered that the loadings selected should allow a full range of termite feeding behaviour, from low loadings that cause no mortality to high loadings that always cause mortality. Six replicates per treatment regime per wood preservative were prepared for each collaborator

Controls: Solvent, water and vacuum oven controls.

Artificial weathering: The treated blocks were subjected to a volatilisation procedure (i.e., 5 days at 40^{o}C in full vacuum), which removed any residual solvent (toluene). Blocks were weighed to determine the initial mass of the treated blocks.

Termite species: There was a different setup for each species of termite per termitologist (Table 1). For convenience in this paper, the word termite refers to subterranean termites.

Termite bioassays: On receipt of the treated blocks, each termitologist set up their own preferred laboratory bioassay and recorded termite mortality throughout their bioassay period. Blocks were returned to Melbourne where they were vacuum oven-dried and weighed. The amount of wood consumed and mean mass loss (%) per loading of wood preservative and the solvent control wood blocks were recorded for all the termite bioassays. The preservative was to be considered acceptable if wood consumption was kept to a mean mass loss of less than 5%..

RESULTS

This study shows that there are considerable differences in the termite test protocols used by the termite researchers in the various countries who agreed to participate in this unique collaborative study of termite bioassays. The termite species used by each collaborator, including the volume of their respective test wood blocks, number of test termites per experimental unit and the test period (days) are summarised in Table 1. All the various laboratories use a Rhinotermitid termite species as their test termite. However, in Australia, apart from the Rhinotermitid, *Coptotermes acinaciformis*, a single member of the Mastotermitidae, *Mastotermes darwiniensis*, is used in laboratory bioassays.

The Japanese test procedures follow the JWPA protocol (see Tsunoda 1986) and are conducted over 21 days. France, the United Kingdom and Thailand follow EN 117 (1990) stipulating 56 days, which is also the test period for the Australian Rhinotermitid protocol (Gay *et al.* 1955). The North Americans (USDA Forest Service, Mississippi and University of Hawaii) follow protocols published in ASTM (1991) and AWPA (1991) and have a test period of 57 days (Grace *et al.* 1993). *Mastotermes darwiniensis* was tested over a 42 day period.

The number of test termites varied considerably. The lowest number used is 100 workers by Mississippi researchers, with the Japanese and Europeans using 165 and 275 respectively. In Australia, 2500 *C. acinaciformis,* and over 490 *M. darwiniensis* are used.

CCA treatments:

The amount of wood consumed (mg wood/g termites/day) in the CCA solvent controls (water) is shown in Table 2. There was a wide variation in amount consumed, ranging from 7.08 to 75.43 (mgW/gT/day). The data showed that even when similar termite protocols were followed, such as in France and the UK, and using the same termite species, *Reticulitermes santonensis,* the French bioassay recorded double the amount consumed compared to the UK bioassay. The Hawaiian *C. formosanus* at 38.39 (mgW/gT/day) consumed more than the Japanese counterpart.

The mean mass loss (g) of the CCA treated blocks indicates the efficacy of all the CCA retentions examined (see Table 3). If the "5% rule of thumb" criterion is invoked to assess whether or not a wood preservative is successful in preventing termite attack and damage, the data in Table 7 shows that the highest amount of treated wood consumed in any bioassay was only 2.7%. Thus, all bioassays indicated that CCA effectively protects wood against termites at the low loading of 0.5 kg/m^3.

Cu-Na treatments:

Comparing the wood block mass loss of Cu-Na solvent controls(white spirit), the data indicates the highest amount of wood consumed was in the Japanese *C. formosanus* bioassay (see Table 4), whereas in the treated controls, *M. darwiniensis* consumed the highest amount of treated wood (see Table 5). Judging from the Japanese and North American results, and especially the Hawaiian bioassay, the mean mass losses (%) suggest that the lowest loading (0.5 kg/m^3) of Cu-Na was insufficient to prevent termite attack and damage (see Table 7). It would have been instructive to have used loadings of 0.125 and 0.25 kg/m^3. While there are variations across the bioassays, given the experimental error involved in conducting such bioassays, it is clear that Cu-Na possesses termiticidal properties even at the lowest loading.

Comparing termite mass with volume of wood blocks used:

The ratio of the volume of wood block to the mass of test termites is quite variable (see Table 6). From a low in the Japanese protocol of 1:66 to a high in the Australian *C. acinaciformis* bioassay of 1:9375.

DISCUSSION AND RECOMMENDATIONS OF IRG 27 TERMITE WORKSHOP, GAUDELOUPE.

The results presented at IRG 27 were inconclusive due to a combination of factors. The collation of the paper was made difficult due to the failure to adhere to the time-frame dispatched to participants earlier (in 1993) and the lateness of receiving laboratory data from several participants in time for submission to IRG 27. Others mentioned the problems associated with termite substrates between the various bioassays, variability between *Reticulitermes* species in Europe and the different duration's of test methodologies. Other important variables include colony vigour, consistency of conditions, time of death of the termite groups, and time of season of the test. There were no chemical assays, and the results were inconclusive for the CCA treated regimes.

It was recommended that another laboratory bioassay be undertaken, using four loadings of CCA, with the highest loading being 0.5 Kg/m^3 (which had been the lowest loading of CCA in the test just concluded), unleached specimens, and three time periods of test (21, 42, and 56 days). DFFP would carry out a preliminary test for assessing the loadings for the repeat test, and using leached and unleached specimens. Furthermore, the bioassay to include choice and no-choice techniques.

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Table 1: Summary of the termite species used by each termite researcher, volume of test wood blocks, number of termites used per unit, and test period (days).

Country of test	**Termite species**	**Volume test block(mm^3)**	**# of termites /unit test**	**Test period days**
Japan	*C. formosanus*	2000	165	21
France	*R. santonensis*	18750	275	56
UK	*R. santonensis*	18750	275	56
Thailand	*C. gestroi*	18750	275	56
Mississippi	*R. flavipes*	3750	100	57
Hawaii	*C. formosanus*	3750	400	28
AustCops	*C. acinaciformis*	37500	2500	56
AustMasto	*M. darwiniensis*	37500	464	42

KEY: AustCops = *Coptotermes acinaciformis*; AustMasto = *Mastotermes darwiniensis*; C = *Coptotermes*; R= *Reticulitermes.*

Table 2: Comparative wood block mass loss of CCA solvent controls (water).

Country of test	Mean wood loss (g)	Period of test (days)	Number. of termites used per test unit.	Individual termite mass (mg)	Mass of termites (g) used per test unit.	Mean wood consumed mg(W)/g (T)/day
Japan	0.2	21	165	3	0.495	19.24
France	1.17	56	275	3	0.825	25.25
UK	0.51	56	275	3	0.825	11.10
Thailand	0.35	56	275	3	0.825	7.46
Mississippi	0.39	57	100	2.8	0.28	24.12
Hawaii	1.30	28	400	3	1.2	38.39
AustCops	3.97	56	2500	4	10	7.08
AustMasto	8.98	42	464	32	15	14.25

KEY: mg (w) = milligrams of wood consumed; g (T)= gram of termites.

Table 3: Comparative wood block mass loss of CCA treated blocks including the solvent controls (water).

Mean mass loss (g) of CCA treated blocks						
Country of test	**0 kg/m³**	**0.5kg/m³**	**1. 0 kg/m³**	**2. 0 kg/m³**	**4. 0 kg/m³**	**Period of test (days)**
Japan	0.20	0.002	0.002	0.008	0.001	21
France	1.17	0.036	0.027	0.016	0.027	56
UK	0.51	0.056	0.012	0.092	0.006	56
Thailand	0.35	0.034	0.091	0.015	0.053	56
Mississippi	0.39	0.026	0.029	0.03	0.014	57
Hawaii	1.29	0.024	0.041	0.044	0.025	28
AustCops	3.97	0.177	0.258	0.182	0.125	56
AustMasto	8.98	0.054	0.115	0.076	0.070	42

Table 4: Comparative wood block mass loss of Cu-Na solvent control (white spirit).

Country of test	**Mean mass wood loss (g)**	**Period of test (days)**	**Total No. of termites used per test unit.**	**Individual termite mass (mg)**	**Mass of termites (g) used per test unit.**	**Mean wood consumed mg(W)/g (T)/day**
Japan	0.18	21	165	3	0.49	17.21
France	0.37	56	275	3	0.83	7.98
UK	0.48	56	275	3	0.83	10.41
Thailand	0.04	56	275	3	0.83	0.93
Mississippi	0.14	57	100	2.8	0.30	9.02
Hawaii	1.15	28	400	3	1.20	12.47
AustCops	2.93	56	2500	4	10.00	5.22
AustMasto	8.86	42	491	32	15.00	14.06

KEY: mg (w) = milligrams of wood consumed; g (T)= per gram of termites.

Table 5: Comparative wood block mass loss of Cu-Na treated blocks including solvent controls (white spirit).

Mean mass loss (g) of Cu-Na treated blocks						
Country of test	**0 kg/m³**	**0.5kg/m³**	**1. 0 kg/m³**	**2. 0 kg/m³**	**4. 0 kg/m³**	**Period of (days)**
Japan	0.18	0.05	0.02	0.02	0.03	21
France	0.37	0.42	0.02	-0.002	0.04	56
UK	0.48	-0.055	-0.03	-0.01	0.03	56
Thailand	0.04	0.09	0.08	0.06	0.10	56
Mississippi	0.32	0.14	0.04	0.03	0.03	58
Hawaii	1.15	0.42	0.24	0.07	0.04	28
AustCops	2.93	0.19	0.16	0.15	0.19	56
AustMasto	8.86	0.11	0.28	0.32	0.32	42

Physical treatments designed to reduce checking were applied to green sample posts before preservative treatment. Treatments were as follows;

(1) Unmodified posts acted as controls (PC)

(2) Boring a 32 mm diameter hole along the central axis of the post (CB)

(3) Incising with a pattern of 8 mm deep, 25 mm long cuts, 25 mm apart in 13 equally spaced rows around the circumference (I)

(4) Cutting one 3 mm wide, 50 mm deep, radial saw kerf (K1)

(5) Cutting two diametrically opposed 3 mm wide, 25 mm deep, radial saw kerfs (K2)

After air drying under cover for ten weeks, the posts were subjected to pressure treatment with 2.4% chromated copper arsenate (CCA) solution. A pilot scale wood preservation plant at the ANU was used to treat the posts. The pressure treatment cycle consisted of 0.5h under a vacuum of -90 kPa, 2h at a pressure of 1380 kPa and 0.5h under a vacuum of -90 kPa.

In addition, a separate set of samples were treated as above with the following;

(1) 2.4% CCA-C, acted as a control (CC)

(2) 2.4% CCA-C and 1.5% polyethylene glycol 1000 (CCA/PEG, CP)

(3) 2.4% CCA-C and after 7 days, an additional CCA-C + 6.5% POEC oil emulsion treatment (Envelope PROCCA, EP)

(4) 2.4% CCA-C + 6.5% POEC oil emulsion (Full PROCCA, FP)

A balanced incomplete block design (with ten replications) was used for the physical treatment trial and a randomised block design with six replications was chosen for the chemical treatment trial.

During the drying period a considerable number of checks developed. Those greater than 1.0 mm in width at their widest point were counted. Treated posts were weighed to determine CCA retentions and held under cover for two weeks to allow for CCA fixation to occur.

Kiln drying (D) at a maximum temperature of 80°C was applied to a batch of unmodified posts after CCA treatment to reduce their moisture content to approximately 12%. The checking of these posts were compared with those subjected to the physical treatments above.

The posts were then racked out horizontally in the open in a random pattern. Each post was rotated 120° every two weeks for the first six weeks and once every four weeks for the rest of the year. After one full rotation (six weeks) checks greater than 1.0 mm wide were again counted. Checks were counted again after one years weathering and their length, maximum depth and width were measured (using a steel ruler and a set of feeler gauges). An estimate of crack volume was calculated from the formula (Maximum depth x maximum width x length)/6, derived by assuming each check could be represented by two right angled prisms back-to-back.

Analysis of variance (ANOVA) was used to determine the effect of the physical and chemical treatments on the number of checks after air drying prior to preservative treatment, after six weeks weathering. ANOVA was also used to determine the effect of the physical remedial treatments on check sizes and numbers after one years weathering. Results are presented graphically and individual means can be compared using least significant differences or 95% confidence intervals. In addition statistical tests were carried out to ascertain whether there were correlations between post mass or growth ring eccentricity and the number of checks after air drying.

RESULTS AND DISCUSSION

Checking during air drying

During air-drying, prior to preservative treatment, checks developed in the posts. The physical treatments were applied to the posts before air-drying and were able, in some cases, to reduce the number of checks greater than 1.0 mm wide that developed (Fig. 1A). An analysis of variance of check numbers showed that the single and double kerfing treatments and center-boring significantly ($p<0.001$) reduced checking compared with posts subjected to kiln drying (effectively a control because kiln drying was carried out after CCA-C treatment) and the untreated control. Check numbers in posts subjected to the two kerfing treatments and center-boring did not differ significantly ($p>0.05$) and check numbers were similar in the center-bored and incised posts. The latter had significantly less checks than the kiln dried posts, but did not differ significantly from the control (Fig. 1A).

Checking after six weeks weathering

After treatment with CCA and six weeks weathering during a hot summer, check numbers in posts increased, but the checks that developed during air drying constituted a large proportion of the total number of checks in the posts (compare Fig. 1B with Fig. 1A). All of the treatments, except incising (I) and kiln drying (D), significantly ($p<0.001$) reduced checking compared with the control; (D) was significantly worse, ie, had more checks. In general, the ability of the treatments to reduce checking after 6 weeks weathering was similar to that observed after air drying, with the exception that single kerfing appeared less effective than either double kerfing or center-boring. On balance, the double kerfing and center-boring treatments were the most effective in reducing the development of checks during the initial period of weathering with single kerfing not quite as effective.

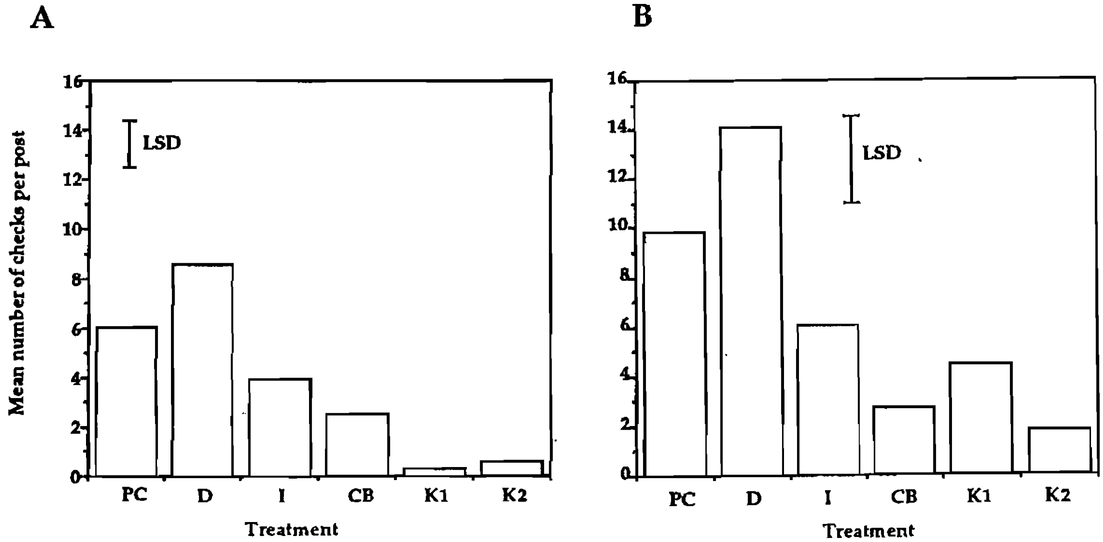

Figure 1. Mean number of checks, greater than 1.0 mm wide, in the posts after ten weeks air drying [A] and after 6 weeks weathering [B] (PC - control, no physical treatment, D - kiln dried, I - incised, CB - center-bored, K1 - one saw kerf, K2 - two saw kerfs.)

Checking after one years weathering

The kiln drying, incising and center-boring treatments did not significantly ($p>0.05$) reduce the number of checks developing in the posts after one years weathering compared with the control, but the single and double saw kerf treatments significantly ($p<0.05$) reduced checking (Fig. 2). If check numbers present after 6 weeks weathering are compared with those present after 1 year (Figs. 1B and 2) it can be seen that check numbers increased in posts subjected to center-boring and double kerfing, remained the same in the controls and incised posts and decreased in the kiln dried and single kerfed posts. Posts subjected to the center-boring and kerfing treatments had reduced check lengths compared to the control, but they were not significantly ($p>0.05$) different from each other (Fig. 3A). The results for check depth, width and volume were slightly different in that kerfing was more effective than center-boring in reducing checking (Fig. 3B, 3C and 3D). Nevertheless the sizes of checks in posts subjected to center-boring were still significantly ($p<0.001$) smaller than in the control. None of the remaining treatments were effective in reducing check size with the exception of check volume in incised posts.

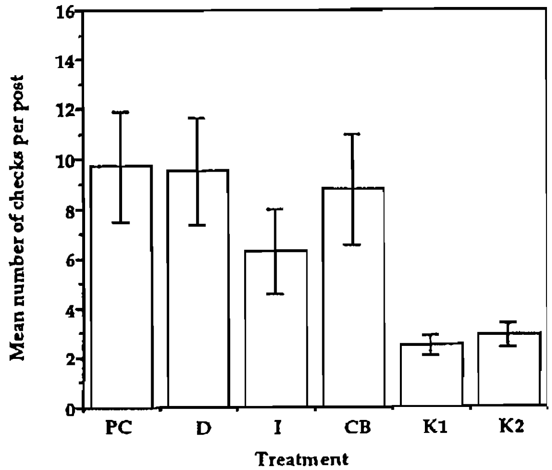

Figure 2. Mean number of checks, greater than 1.0 mm wide, in the posts after one years weathering. (PC - control, no physical treatment, D - kiln dried, I - incised, CB - center-bored, K1 - one saw kerf, K2 - two saw kerfs.) Bars represent 95% confidence intervals.

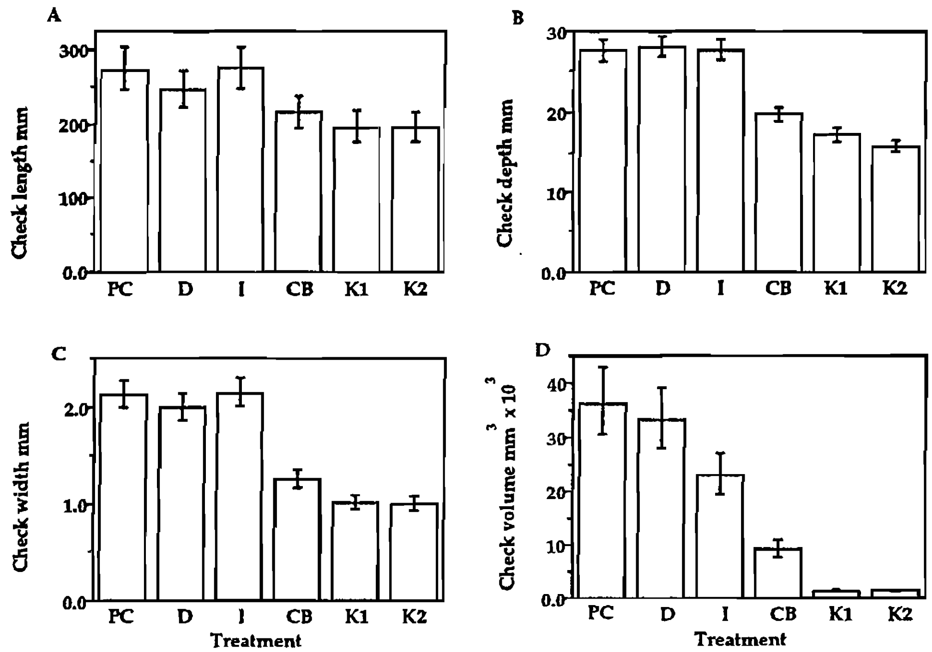

Figure 3. Mean values for A, check length; B, check depth; C, check width and D, check volume after one years weathering. (PC - control, no physical treatment, D - kiln dried, I - incised, CB - center-bored, K1 - one saw kerf, K2 - two saw kerfs.) Bars represent 95% confidence intervals.

Treatment with modified CCA solution did not significantly ($p>0.05$) reduce the number of checks in the posts after one years weathering compared to the treated controls (CC). The finding that treatment of posts with CCA-oil emulsion did not reduce checking accords with previous research (Ruddick 1981) on checking in white spruce (*Picea glauca* (Moench) Voss) poles which indicated that 'the use of oilborne preservatives alone will not prevent the formation of deep checks'.

The finding that single kerfing significantly reduced checking in CCA treated pine posts after 6 weeks and 1 years weathering accords with previous work (Graham 1979, Helsing & Graham 1979, Morell 1990, Ruddick & Ross 1979), but single kerfs tended to open very wide (>10 mm) in dry weather, a feature which may adversely affect the acceptance of such posts. For this reason, double kerfing, which was equally effective in reducing checking, may be a more commercially acceptable treatment. Deep incising is reported to be effective in reducing the checking of softwood poles, but shallower incisions, similar in depth to those used in this study have been found to be less effective (Perrin 1978). Hence it is not surprising that incising here had little effect in reducing checking. A previous study by Goodell and Pendlebury (1990) found that center-boring was ineffective in reducing checking in CCA treated red spruce poles after 1 years exterior exposure, even though it reduced the size of checks in untreated controls. This is not consistent with results here in which center-boring was clearly effective in reducing check sizes in CCA treated slash pine during exterior exposure. The reason for this discrepancy is not known, but it indicates that further work with other timbers and a larger range of preservative types, particularly the newer waterborne preservatives such as ammoniacal copper quaternary (ACQ) and copper azole compounds, is necessary to obtain a more complete understanding of the ability of physical treatments to reduce the checking of preservative treated roundwood during exterior exposure.

CONCLUSIONS

1. Single and double kerfing and center-boring were effective in reducing the number of drying checks greater than 1.0 mm wide in slash pine posts before preservative treatment. There appeared to be a useful correlation between the post green mass before air drying and the number of checks after air drying. Culling a proportion of the heavier green posts, assuming all the posts are the same size, may lead to a useful reduction in the mean number of checks in the remaining posts after air drying.

2. Double kerfing and center-boring were the most effective treatments in reducing the development of checks after the posts were treated with CCA and subjected to six weeks weathering; single kerfing was less effective.

3. After one years weathering, center-bored and single and double kerfed posts showed less checking than the corresponding controls and kiln dried and incised posts (except for mean number of checks in the center-bored posts). The single and double saw kerf treatments did not differ significantly in terms

of their ability to reduce check numbers and sizes and both were significantly better than the other treatments (except for mean check length in the center-bored posts). The incising and kiln drying treatments were ineffective in reducing checking after air drying or weathering. The chemical treatments were ineffective in reducing checking in the posts after one years weathering.

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OPTIONS FOR THE DISPOSAL OF CCA TREATED TIMBER

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ABSTRACT

The results of two studies are presented concerning the options for the disposal of CCA treated wood waste. One investigation assesses the leaching and fate of copper, chromium and arsenic from treated wood exposed to weathering in field lysimeters. The other study reports on the combustion of CCA wood blended with other wood waste and the recovery of CCA from the residual ash. The two studies indicate that options exist for the disposal of CCA treated lumber that minimise environmental impacts. However, further research is required to optimise their use in industrial situations.

INTRODUCTION

Although timber products treated with copper, chromium and arsenic (CCA) have long service life (up to 50 years), at some time in the future their use becomes redundant due to mechanical damage or failure, biological deterioration or replacement. At this time, the material will be withdrawn from service and be either reused, abandoned or require disposal. Other sources of CCA treated wood waste arise from the processing of treated timber into final shape and form at wood processing sites, timber remanufacturing operations and construction sites.

Although CCA treated wood is frequently disposed of into landfills in New Zealand, such practices are becoming increasingly controlled through the Code of Practice for the Use of Timber Preservatives (Department of Labour 1994) or such wastes are being classified by landfill operators. The Department of Labour's Code stipulates that CCA treated off-cuts, shavings and sawdust wastes "shall be disposed of by way of regional council consent or as otherwise authorised, eg in an approved landfill".

Two studies being undertaken in New Zealand related to the disposal options for CCA treated wood are:

- an assessment of the leaching and fate of CCA from treated wood exposed to medium to long term leaching, and
- the combustion of CCA wood waste and recovery of copper, chromium and arsenic from the residual ash.

Results from these investigations are reported in this paper.

LEACHING AND FATE OF CCA FROM TREATED WOOD

Many studies have been undertaken on the loss and depletion of CCA from treated products to determine their leaching characteristics, the efficacy of treated product and potential environmental effects from leached chemical (Cooper 1991,1994; Murphy and Dickinson 1990). However, there is little published information on the leaching of CCA from 'aged wood' (potential CCA treated wood waste) when dumped and exposed to natural weathering conditions over the medium to long term. The objectives of this study were to assess the leaching of CCA from wood waste, the potential of CCA to adsorb onto soils and the quality of leachate when CCA treated wood was exposed to natural weathering conditions. Results from the first fourteen months of exposure are discussed here, though this study will continue for at least a further two years.

Methods

The leaching trials were undertaken using lysimeters constructed from 300 mm diameter PVC pipe and cut to 600 mm lengths. The lysimeters were filled, bottom to top, with a 200 mm intact soil core, typical of the central North Island volcanic plateau, 20 mm of sand and 300 mm of H3 (retention level of approximately 6 $kg.m^{-3}$) CCA treated wood chips. The soil was a sandy/silt tephra, with a low organic content (11.4%) and relatively low cation exchange capacity (23 me/100g). The CCA treated chips were sourced from wood treated using a commercial Bethell full cell process and type c CCA salt formulation. Leachate from the lysimeters was collected from a drain at the bottom of the lysimeters. Prior to installing the chips into the lysimeters, the wood was weathered for 2 months.

In total, 36 lysimeters were installed, twelve contained CCA treated wood chips and soil, eleven were filled with untreated wood chips and soil, eleven contained sand (which replaced the wood) and soil, 1 contained CCA wood waste and 20 mm sand and 1 was empty. The lysimeters containing the untreated wood and sand were controls for the effect of the CCA on the soil, and wood on the soil respectively. The CCA wood waste and sand lysimeter (ie no soil) indicated the effect soil had on the leachate quality and the empty lysimeter was sampled to assess the chemical composition of the rainwater.

Data collected for each lysimeter included the amount (kg dry weight) of wood and soil placed into each lysimeter, the inorganic composition of the wood and soil and the physical characteristics of the soil. Samples of leachate from the lysimeters were collected after rainfall (10 ml of leachate per 1 mm of rainfall) to assess leachate quality. The collected leachate was composited over two monthly periods to give sequential two monthly leachate composite samples for chemical characterisation. Three replicate lysimeters were sampled for the CCA, untreated wood and sand treatments. Leachate analyses included assessment of the inorganic composition using ICAP, pH, total dissolved solids, total organic carbon, Microtox® toxicity and colour. Hexavalent chromium was assessed for one sampling period. The total concentrations and mass for CCA are reported.

To assess the extent of leaching from the CCA treated wood, three of the lysimeters containing CCA treated wood chips were harvested and the wood and soil were analysed for their inorganic chemical content. These analyses indicated any change in the

CCA concentration of the wood and soil due to weathering and adsorption. The lysimeters were established initially during April 1995 and the first set of lysimeters containing CCA treated wood and soil was harvested in October 1995.

Results

Only a selection of the results are presented that indicate the effect that natural weathering had on the movement of CCA from treated wood in the field lysimeters and the impact of soil adsorption on CCA concentrations of the leachate.

The average leachate yield from the lysimeters containing either wood chips or sand ranged from 248 - 259 $mL.day^{-1}$, which was equivalent to approximately 110 litres over the 422 day period that the lysimeters were exposed. The leachate yield from the lysimeters with sand and chips was lower than for the empty lysimeter. Both sand and chips caused an approximate 20 percent loss of water through evaporation or other processes. The low leachate yield from the CCA and sand lysimeter is unexplained at present.

Table 1. Leachate yields from the lysimeters

Lysimeter description	Mean leachate yield ($mL.day^{-1}$)
Empty	340
Sand + soil	259 (11.7)
Untreated + soil	250 (57)
CCA + soil	248 (31)
CCA and 20 mm sand (no soil)	190

( ) indicates the 95% confidence limits for the leachate yields (n = 3).

The leachate from the different lysimeters was found to contain copper (Cu), chromium (Cr) and Arsenic (As) with the lysimeter containing CCA (no soil) having the highest concentrations of each constituent (Figure 1). Arsenic was found to leach the most and Cr leached more than copper (based on the mass of element leached). The presence of soil in the lysimeters reduced the concentration of Cu, Cr and As by up to 15 times in the leachate. The soil adsorbed both Cu and As to such an extent that the concentration of these components in the leachate from the CCA and untreated wood lysimeters were comparable. However, the soil adsorbed Cr to a lesser extent. Chromium was the most concentrated component in the leachate from the lysimeters containing the soil cores. Hexavalent chromium was less than 0.005 $mg.L^{-1}$ in the leachate from the lysimeters containing the CCA material.

Both the concentration and total mass of Cu, Cr and As found in leachate from the lysimeters over the April 95 to June 96 period showed seasonal trends and their minimums occurred during April (Figure 1). The apparent seasonal trends were attributed to the amount and frequency of rainfall, temperature and the progressive loss of Cu, Cr and As from the wood. A comparison between the concentration and total mass graphs

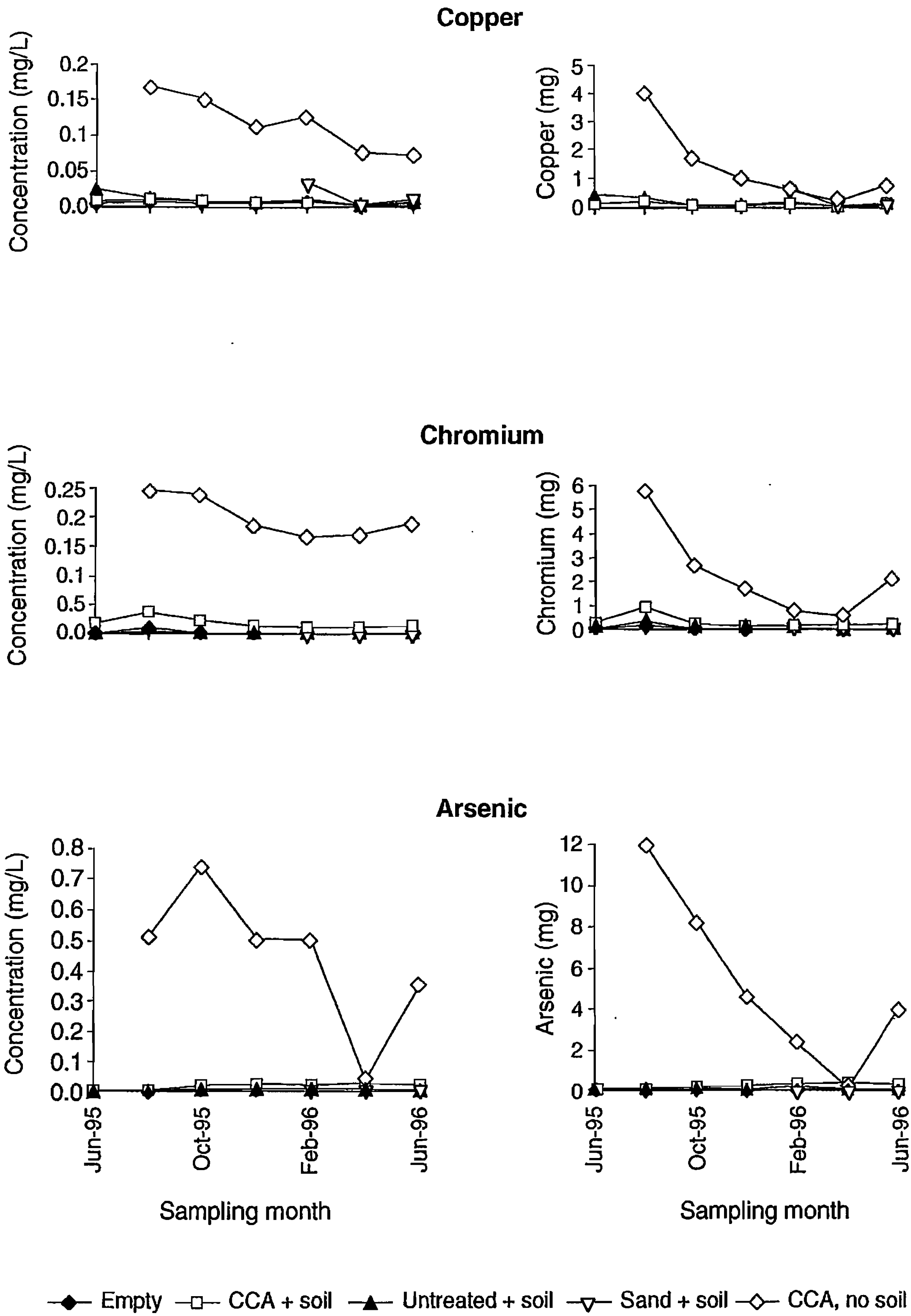

Figure 1. Concentration and total quantity of Cu, Cr and As leached from the field lysimeters

showed that the changing concentrations over time were real and were not directly attributable to varying leachate yields which caused dilution of the Cu, Cr and As.

Only one series of lysimeters had been harvested by June 1996 to determine the relative partitioning of Cu, Cr and As between the wood, soil and leachate. Analysis of the collected rain in the empty lysimeter enabled an assessment from this contribution as well. For each of the three elements, only a small proportion (0.007 - 0.011 percent) of the chemical was leached from the lysimeters and the chromium content of the soil was found to increase the most (Table 2). There was a small increase in the amount of arsenic in the soil, whereas the copper concentration appeared to decrease. The decrease in Cu may not be real and has been attributed to the low leaching of copper, uncertainty in determining the copper concentration in the soil samples and the lower quantity of copper present in the initial wood.

Table 2. Distribution of copper, chromium and arsenic in lysimeters (mean percentages for the three lysimeters harvested and containing CCA treated wood chips and soil).

	Initial April 1995	Final October 1995
Copper		
- Wood waste	98.4	98.96
- Soil	1.6	1.02
- Rain		0.012
-Leachate		0.008
Chromium		
- Wood waste	99.9	99.802
- Soil	0.1	0.185
- Rain		0.002
-Leachate		0.011
Arsenic		
- Wood waste	98.8	98.660
- Soil	1.2	1.330
- Rain		0.003
-Leachate		0.007

Initial values indicate the relative amount of Cu, Cr and As in the different components of the lysimeters when originally installed (April 1995). The final values indicate the relative partitioning of Cu, Cr and As in October 1995 after 6 months weathering.

Conclusions from the Leaching Studies

A small proportion of the Cu, Cr and As (approximately 0.008, 0.011 and 0.007 percent respectively) in the lysimeters (CCA treated wood chips and contributions from rainfall) is leached following exposure to natural wetting and drying cycles. Arsenic leached to the greatest extent from the wood but was readily adsorbed by the soil. Chromium was the next most leached component from the wood, but was the least adsorbed by the soil. The leaching of Cu, Cr and As appeared to be influenced by climatic variables though ongoing monitoring is required to verify this. Wood chips markedly affected leachate yields by absorbing water and acting as an effective medium for evaporation. The results from the lysimeter studies indicated that landfill disposal of CCA treated wood is likely to be a safe practice as the soil will readily adsorb leached chemical and result in the leachate having low concentrations of Cu, Cr and As. Further research is required to assess the adsorptive potential of other soils.

DISPOSAL OF CCA TREATED WOOD AND RECYCLING OF CCA USING COMBUSTION

Although the landfilling of CCA treated wood is a safe practice, a combination of increased landfilling costs and the reduced availability of landfill space are encouraging the assessment of alternative disposal options for these materials. One such option is to burn the waste wood to recover energy and potentially recycle Cu, Cr and As from the ash back into the wood preservation process. Incineration has been considered as a viable option for the disposal of CCA treated wood (Pasek and McIntyre 1993, Ruddick 1994, Nurmi 1996). However, environmental risks from the loss of volatile components in the air emissions, in particular arsenic, and the disposal of contaminated ash can cause environmental concern.

A number of studies have already considered the volatile losses of As arising from the combustion of CCA treated wood (Watson 1958, Dobbs and Grant 1976, 1978). Pohlandt *et al.* 1993 have reported on the leaching of Cu, Cr and As from ash. The investigation reported here assessed the effects that the co-combustion of CCA treated material, blended with an excess of clean wood and bark, had on the release of volatile inorganic components and the leaching behaviour of Cu, Cr and As from the residual ash.

Methods

Four different fuels were prepared using blends of CCA treated material and a mixed wood waste fuel. The wood waste fuel consisted of equal proportions of radiata pine bark and wood. The CCA treated wood was from the same source as used for the lysimeter experiments. All fuel materials were dried to 80 % oven dry content (20% moisture) prior to blending. The four fuels consisted of a standard wood waste fuel (equal proportions of bark and wood chips); 1% w/w CCA treated material and 99% w/w prepared wood waste; 5% w/w CCA treated material and 95% w/w prepared wood waste; 100% w/w CCA treated material. Fuels were blended through a hogger with a 17 mm screen.

Combustion trials were undertaken using a small laboratory based understoker unit. Flue gases passed through an extended duct to cool and equalise flow prior to sampling. The unit was equipped with continuous monitoring of air flows, emission flow rates, combustion and stack temperatures and products of combustion (for example CO_2, CO and N_2O). A sample of the flue gases was taken isokinetically through a heated quartz tube and passed through solvent trains to collect volatile inorganic components. Each train consisted of two chilled impingers in series, one train contained 2% nitric acid and the other 0.1M sodium acetate.

Each trial (ie combustion of each fuel) ran for 10 to 13 hours and consumed 80 to 100 kilograms of fuel. The trials were undertaken in order of the increasing content of CCA treated material. At the completion of each run all ash, particulates and the impinger samples were analysed and the results were used to determine mass balances for the inorganic components. Samples of the residual ash were leached using a modified Toxicity Characteristic Leaching Procedure (US EPA 1990) which was used to indicate changes in the leaching behaviour of Cu, Cr and As from ashes arising from the combustion of the different fuel blends. Only results relevant to the recovery, partitioning and leaching of Cu, Cr and As are considered here.

Results

Analysis of the final fuel blends used for each of the combustion trials (Table 3) showed that the relative ratios of CCA treated material to prepared wood waste were close to the original targets (ie 1 and 5%). The relative ratio of copper, chromium and arsenic in the original CCA treated material was 24:45:31 respectively.

Table 3. Concentration of copper, chromium and arsenic in the original fuel blends.

Constituent $mg.kg^{-1}$	Wood waste	1% CCA	5% CCA	100%
Copper	4.0	16.7	54.4	1078
Chromium	2.5	29.9	108	2031
Arsenic	4.7	17.9	69.2	1436

The effect of burning different ratios of CCA treated wood and the prepared wood waste fuel on the partitioning of Cu, Cr and As between the bottom ash (ash), flue gas emissions (flue) and particulates (part) emitted with the flue gases is shown in Table 4. The sum of the three values is the percentage recovery for that element in the particular combustion trial. Recoveries for the different elements ranged from 10 to 104 %, but overall recoveries were regarded as being satisfactory and were around 60 to 70%. The low recovery for As for the control fuel (10%) reflected the low concentration of this element in this sample and values were close to the limit of quantitation. Low recoveries were also obtained for the more volatile arsenic when burning the other fuels. Although the reduced proportion of As in the ash for the 100% fuel indicated that the nature of the fuel influenced the partitioning behaviour of arsenic, this was not supported by finding a lower ratio of As to Cu and Cr in this ash. Both Cu and Cr appeared to be more volatile when burning the 100% fuel as indicated by the lower recoveries.

Table 4. Partitioning of Cu, Cr and As into ash, flue gas and particulates from the combustion of the different wood waste fuels (expressed as a percentage of the original amount of chemical present in the fuel wood).

	Control				1% CCA				5% CCA				100% CCA			
	Ash	Flue	Part	Rec	Ash	Flue	Part	Rec	Ash	Flue	Part	Rec	Ash	Flue	Part	Rec
Cu	33	ND	5	38	72	ND	3	75	73	ND	4	77	66	1	2	69
Cr	76	ND	1	77	101	ND	3	104	101	ND	3	104	81	ND	2	83
As	8	ND	2	10	32	ND	31	63	31	ND	24	55	24	18	14	56

Ash = bottom ash fraction, Flue = flue gas emissions, Part = particulates, Rec = percentage recovery
ND = not detected

There are a number of factors which may influence the partitioning of elements between the ash and flue emissions such as combustion conditions, type of combustion system and fuel quality. Although these results suggested that altering the fuel quality may change the partitioning of arsenic into the ash fraction, the results were inconclusive and need be verified with further combustion trials. Furthermore, combustion conditions in an industrial furnace may give different results - an issue also requiring follow up study.

The leaching tests of the final ashes showed that As was the component most readily leached followed by Cr and then Cu (Table 5). The relative proportion of As leached increased with an increase in the amount of CCA wood included in the fuel, whereas Cr and Cu remained unchanged. Copper leached to a negligible extent from the ash samples. These results suggest that recovery of Cu, Cr and As from ashes resulting from the combustion of CCA treated wood by simple leaching methods is limited and variable depending on the nature of the feedstock. Further research is required to develop alternative leaching conditions to recover greater quantities of Cu, Cr and As and to determine factors affecting the leaching of CCA from the ash matrix.

Table 5. Relative proportion of Cu, Cr and As leached from ashes (expressed as a percentage of the amount of each element present in the ash collected after each combustion trial).

Element	Control	1% CCA	5% CCA	100% CCA
Cu	ND	ND	ND	ND
Cr	ND	15	15	16
As	ND	16	36	64

ND = not detected

Conclusions from the Combustion Studies

The results from these combustions trials were consistent with previous work as arsenic was found to be the most volatile component when CCA treated wood was burned. However, evidence was obtained that fuel quality may influence the extent to which As is volatilised and emitted with the flue gas. Further investigations are required to determine optimal fuel mixes and combustion conditions which may be used in industrial wood waste combustion systems to minimise or eliminate As emissions in the flue gases. Arsenic and Cr can be recovered from the ash using simple leaching procedures, but the relative quantities recovered compared to the total amount in the ash were low and variable, depending on the fuel quality and combustion conditions.

Concluding remarks

The environmental performance of CCA treated lumber is likely to come under increasing scrutiny as regulatory agencies and consumers become more environmentally aware. To assess the environmental effects arising from the use of CCA treated lumber, information on the disposal of these materials is becoming critical. The two studies reported indicate that there are options for the disposal of CCA treated lumber that will minimise environmental impacts, but further research is required to optimise their use for wide scale application.

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THE EFFECTS OF NaCl CONCENTRATION ON BASIDIOSPORE GERMINATION AND HYPHAL GROWTH OF *Rigidoporus lineatus*

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ABSTRACT

The effect of salinity on in vitro spore germination and hyphal growth of *Rigidoporus lineatus* (Pers.) Ryvarden was investigated. Basidiospore germination was delayed and reduced by increasing NaCl concentrations. No spore germination was recorded after 9 days on media containing NaCl concentrations greater than 4%. Hyphal growth of *R. lineatus* on agar media was reduced by NaCl concentrations up to 2%. No growth was recorded on 2% NaCl media. The results are discussed in the context of the spread of fungal infection in logs stored under saline water sprays.

INTRODUCTION

The occurrence of severe infestation of *Pinus elliottii* Engelm. timber in the Beerburrum log storage facility by the white rot decay fungus *Rigidoporus lineatus* (Pers.) Ryvarden coincided with a reduction in the salinity of the dam water used as a source for the water sprays. In order to determine whether this reduction had allowed the fungus to become established or to grow from existing but relatively inactive infections, the effect of increasing salinity was investigated on the germination of spores and growth rates of *R. lineatus*.

High concentrations of inorganic salts are known to inhibit spore germination and growth of fungi through both osmotic and fungitoxic action, however lower concentrations of some salts, including NaCl, may have stimulatory effects (Griffin, 1972; Saleh-Rastin, 1976; Sterne *et al.*, 1976). Tatsuyama *et al.* (1968) investigated the survival and growth of five wood decay fungi exposed to various salinities and found that a 1/2 dilution of sea water killed 3 of 5 test fungi and reduced the growth of the other two, full sea water causing a slightly greater reduction in growth. Griffin (1972) reviewed the influence of osmotic and water potential on several aspects of fungal biology and more specifically, on wood decay fungi (Griffin, 1977). He stated that a decrease in water potential was associated with an increase in the latent period before spore germination occurs and at low potentials spores will not germinate.

Maximal growth rates for fungi are recorded at slightly reduced water potentials. Decreasing water potential leads to a reduction in the rate of growth until a point at which growth ceases. The variations in response to decreasing water potential between different fungal species is considerable and may be further affected by other environmental factors. Griffin (1972) reported that the effects of water availability on fungal spore germination and growth was strongly influenced by nutrient concentration, *p*H, temperature and the age of the spores. Other authors have noted the effect of relative humidity, fungicidal chemicals, plant extractives, gaseous regimes and interactions with other fungi or bacteria (Rayner and Boddy, 1988). Therefore, it was necessary to determine the limiting salt concentrations for germination and growth of *R. lineatus.* Sea water has a concentration roughly equivalent to 3.2% to 3.5% NaCl and the water used to spray the logs in storage had concentrations ranging from 0.2% to 1.25% NaCl.

MATERIALS AND METHODS

Media containing Oxoid malt extract (1.25%) and Oxoid agar technical No. 3 (2%) were made up with a range of NaCl solutions or filtered sea water dilutions in distilled water and adjusted to *p*H 6. All media were sterilised by autoclave and all plates were made up with an equal volume (15 ml) of each medium. The range of salt concentrations used was between 0% and 9% NaCl and 33%, 67% and 100% sea water dilutions. This range of concentrations was chosen to provide data on the effect of the recorded historical variations in salinity of the dam water on fungal growth and spore germination. Additionally it would provide some insight into the effects of increasing the water spray salinity to that of undiluted sea water or higher as a potential control measure to limit the spread of the *R. lineatus* infection.

The effect of salt concentration on in vitro spore germination of *R. lineatus*.

Approximately thirty fresh sporophores of *R. lineatus* were collected from a number of infected logs at various sites within the Beerburrum log storage facility. The fruiting bodies were placed in open plastic containers and transported to the QFRI laboratories at Indooroopilly. The sporophores were rinsed briefly with sterile distilled water to remove debris and placed on racks above sterilised plastic trays and covered with plastic film to increase humidity and reduce desiccation of sporophores and spores. The sporophores were left in this position overnight, approximately 18 hours, in order to allow a sufficient quantity of basidiospores to be collected. The spores were rinsed from the bottom of the containers with 100 ml of sterile distilled water containing 500 ppm Tween 80, to aid dispersal of clumped spores, 100 ppm streptomycin sulfate and 100 ppm penicillin-G, to inhibit bacterial growth and contamination. This spore suspension was filtered with a sterile 1.2 μm cellulose membrane filter to further reduce bacterial contamination. Bacteria pass through the 1.2 μm filter but the basidiospores of *R. lineatus* with dimensions of 5 x 4.5 μm (Pegler and Waterston, 1968) are retained on the filter. Harvested spores were washed from the filter with a further 10 ml of distilled water and the process repeated. The final rinse was made with 10 ml of distilled water containing 250 ppm Tween 80.

The resultant concentration of spores in the suspension was measured using a haemocytometer. The concentration of basidiospores was calculated as 3750 - 4250 ml^{-1}. Three replicate plates of each media were inoculated with 0.1 ml of suspension which was spread evenly over the surface with a sterile glass rod. The plates were incubated in darkness at 27°C for 9 days. Spore germination was assessed by direct microscopic examination of the agar surface after 0, 2, 5 and 9 days. Percentage scores were determined by examining three randomly selected fields of view of each plate and totalling the number of germinated and ungerminated spores. Successful germination was recorded when germ tube length exceeded the greatest diameter of the spore. Mean values were calculated from counts made of all replicate plates. The concentrations of salt and sea water in media used in the germination studies were; 0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 7, 8 and 9% NaCl and 1/3 and 3/3 sea water.

The effect of salt concentration on in vitro growth of *R. lineatus*.

Three isolates of *R. lineatus* were selected from several cultures grown from infected logs. The three were chosen on the basis of exhibiting growth representative of all the isolates in the QFRI culture collection. Agar plugs, 5 mm in diameter, were taken from the margin of actively growing cultures and used as inocula for the growth rate studies. Plates were inoculated centrally and incubated in darkness at 27°C for 8 days at which time the final extent of radial growth was recorded. Growth was assessed by measuring hyphal extension across the plate. Two diameters were measured for each of two replicate plates for each isolate of *R. lineatus*. Daily growth rates were calculated as a mean for each isolate and an overall mean. The concentrations of salt and sea water in media used in the growth rate studies were; 0, 1, 2, 3, 4.5, 6 and 9% NaCl and 1/3, 2/3 and 3/3 sea water.

RESULTS

The effect of salt concentration on in vitro spore germination of *R. lineatus*.

Spore germination occurred rapidly with over 75% germination recorded in media containing 0 to 1% NaCl and 33% sea water after 2 days. With increasing salt concentration spore germination decreased and no germination was visible on media containing 4% or more NaCl. By day 5 many of the plates were being over grown by mould fungi and bacteria, data for days 5 and 9 represent germination on uncontaminated plates only. Percentage germination increased between day 2 and 5 in all media with NaCl concentrations of 4% or less. The most significant increases were recorded in media containing undiluted seawater or 3.5% or 4% NaCl. Germination on these media increased from virtually nothing to 87%, 57% and 30% respectively. By day 9 most plates were contaminated and only a slight increase in percentage germination was recorded in the 4% NaCl medium. Figure 1 presents the mean percentage germination data for all media at each assessment.

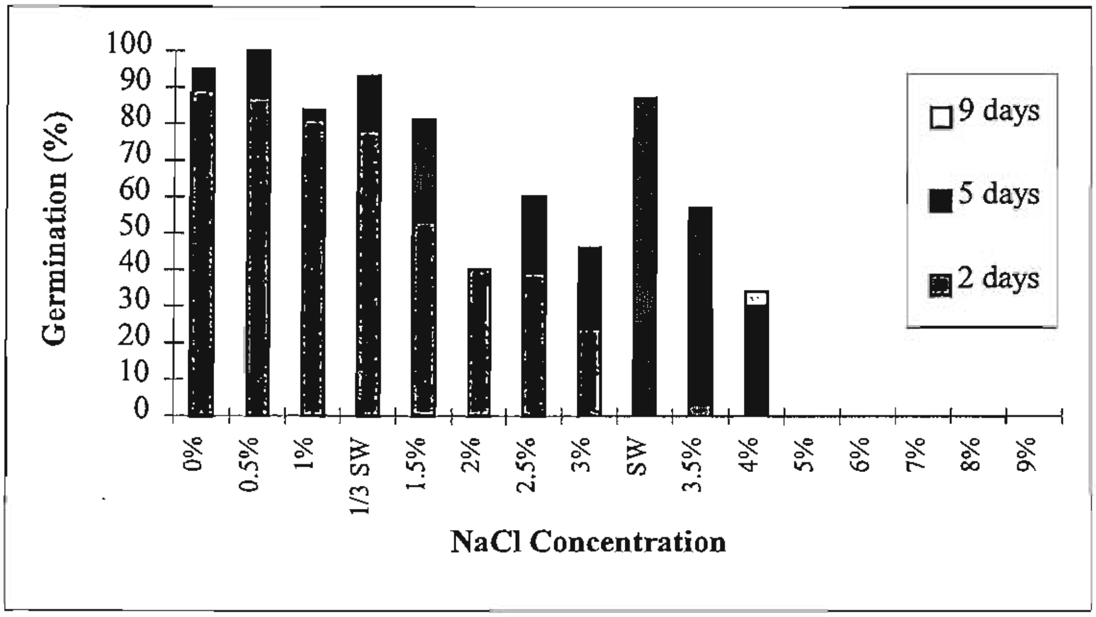

Figure 1. Increases in mean percentage germination of *Rigidoporus lineatus* basidiospores on agar media containing various concentrations of salt (NaCl) recorded after 2, 5 and 9 days incubation.

The effect of salt concentration on in vitro growth of *R. lineatus*.

As with spore germination, hyphal growth of *Rigidoporus lineatus* showed an inverse relationship to the concentration of salt present in the media. The individual growth rates of the three isolates of *R. lineatus* showed some variation but the effect of salt concentration was consistent. Colonies grew most rapidly on a salt free medium. Control plates with no added salt exhibited almost full plate cover after 8 days. Media containing salt concentrations of 1% or 1/3 seawater exhibited a reduction in growth of approximately 30%. On media with a 2% NaCl concentration or seawater at 2/3 dilution hyphal growth was markedly reduced, the mean growth rates at these concentrations showing approximately 75 to 80% less growth than controls. All three isolates grew on media containing up to 2% NaCl. No growth was recorded on media with salt concentrations of greater than 2% or 2/3 dilution of seawater. At concentrations of 3% NaCl and greater no hyphal growth was observed and the diffusion of salt into the agar core appeared to have killed the inoculum. The results of the growth rate experiment are presented in Figure 2.

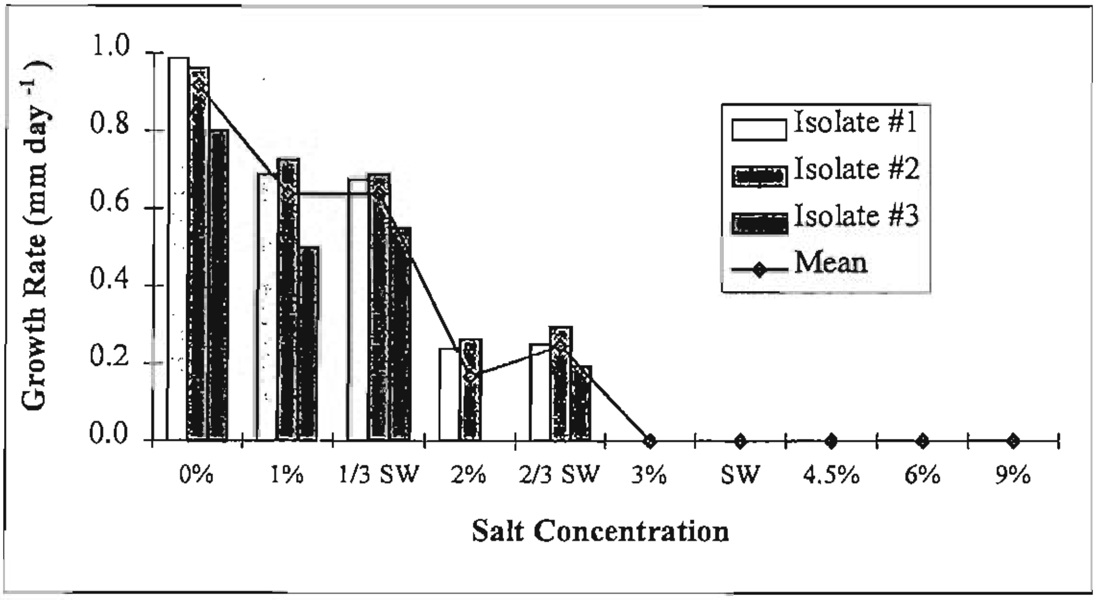

Figure 2. Effect of salt concentration on the in vitro growth rate of three isolates of *Rigidoporus lineatus* incubated at 27 °C for 8 days.

DISCUSSION AND CONCLUSIONS

The presence of salt, either as NaCl or sea water, in agar media inhibited both germination of basidiospores and hyphal growth of *R. lineatus* in vitro. The inhibitory effect increased with increasing salt concentration. Continuing investigations by the authors have shown that similar media containing 3% and 4% NaCl are at approximate water potentials of -28 and -36 bar, respectively (unpublished data). Water potential is a function of osmotic potential, matrix potential, gravitational potential and the effect of external pressure (Rayner and Boddy, 1988). In this series of experiments the matrix potential of the agar media calculates to approximately -5 bar, the remaining potential is due to the osmotic effect of the salt concentration, all other contributions being efectively negligible.

The results presented here indicate that under these experimental conditions there is no latent period for germination of *R. lineatus* basidiospores on media containing NaCl concentrations equivalent to or less than 1/3 sea water. The latent period was less than 3 days on media with NaCl concentrations equivalent to and greater than sea water up to 4% NaCl. Germination had not occurred on agar media at concentrations of 4% NaCl (-36 bar) or greater by day 9. These results are typical of wood decay fungi, Merrill (1970) stated that under normal environmental conditions, high percentages of basidiospores of most wood attacking Hymenomycetes germinate within 24 hours. Spore germination is a complex process but is known to be dependent on water potential. Decreased water potentials, together with a host of other environmental factors, may lead to an increase in the length of the latent period before spore germination takes place (Griffin, 1972) but these generally occur only at very low water potentials with associated latent periods of 70 days or more. Mould and bacterial contamination of media prevented any long term assessment of latency in this investigation.

The hyphal growth rate of *R. lineatus* was negatively correlated with increasing salt concentration. Growth was reduced by 25% on a 1% NaCl medium (at an approximate water potential of -13 bar), by 80% on a 2% NaCl medium (-20 bar) and was not observed on media at salt concentrations equal to or greater than 3% NaCl (-28 bar). These results agree with Griffin (1977), who concluded that the lowest osmotic potential for growth of most wood-rotting basidiomycetes to be about -40 bar with a 50% reduction in growth at -15 bar, and Wilson (1973), who reported that 5 of 6 basidiomycetes tested did not grow at -30 bar.

The salinity of the dam water used at Beerburrum as a source for the water sprays has been continuously monitored through measurement of conductivity. This data shows that, in the month prior to January 1996 and the discovery of *R. lineatus* in the wet stored timber, NaCl concentrations in the dam water fell from approximately 1% NaCl, down to an equivalent concentration of 0.25% NaCl. Maximum salinity levels in the dam water, representing approximately 1.25% NaCl, were recorded during the period October to November 1995, minimum levels of 0.2% NaCl were recorded during February 1995 (Lynch, 1996). Though the NaCl concentrations recorded in the dam water do not represent sufficiently low water potentials to cause any significant delay or decrease in spore germination, the growth of mycelia observed under the bark on water stored logs may have been slowed by up to 25%. The drop in salinity recorded just prior to the discovery of *R. lineatus* is unlikely to have been the significant factor that allowed infection to take place. It may have allowed slightly faster mycelial growth and quicker germination of spores and an acceleration in the spread of the fungus. However, these results were recorded on agar media and are therefore not directly relevant to spread of the fungus in or on wood.

The results suggest that increasing the salt concentration in the sprays at the log dump may inhibit the spread of the fungus through inhibition of spore germination and reduction in growth rate. However, the salt concentration required to completely prevent spread by spores and surface mycelium would be approximately 3% NaCl or full sea water. Wood absorbs salt rapidly from saline water (Maclean and Macdonald, 1968) and the salt concentration in the wood in the log storage facility would eventually equilibrate with the salt concentration of the spray water. The concentration of salt in the water sprays affects the quality and properties of the timber and should 3% NaCl concentrations or higher be used there are possible limitations to the end use of the stored timber, for example; the unsuitability for the kraft pulping process due to elevated chloride levels (Backwell and Hitzroth, 1992; Gleadow *et al.*, 1993) and problems in use as utility poles associated with increased conductivity (Maclean and Macdonald, 1968). Additional considerations were the increased cost of maintaining high NaCl concentrations in an essentially open system subject to heavy rainfall dilution, and finally the possibility of marine borer infestation with increased storage time. Thus, it was concluded that permanently raising the salinity of the water sprays was inadvisable.

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THE OCCURRENCE, DEVELOPMENT AND SIGNIFICANCE OF DECAY IN STORED LOGS CAUSED BY *Rigidoporus lineatus*.

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ABSTRACT

In January, 1996, decay caused by *Rigidoporus lineatus* was found in salvaged logs of slash pine (*Pinus elliottii* var. *elliottii*) stored under water sprinklers following fires in plantations at Beerburrum in south east Queensland in September and November, 1994. In March the incidence of logs with fungal fruitbodies varied between 5% and 100% in different bays. Incidence and amount of decay varied along the bays, was greater deeper in the log piles, and initially appeared lower in logs salvaged after the appearance of sapstain. Colonies of *R. lineatus* formed dark brown zones within the sapwood frequently associated with ends and debarked areas along the undersides of logs. White, branching, mycelial fans were present beneath the bark coincident with the brown zone, and branching mycelial cords grew across the bark surface. Advanced decay formed a white pocket rot.

Isolates of *R. lineatus* showed optimum growth over the range 22-30°C. Growth rates decreased only slightly as oxygen levels were reduced, whereas those of cultures of decay fungi obtained from pine log debris in adjacent plantations declined significantly. *R. lineatus* therefore appears better adapted to maintaining growth in the reduced oxygen regime present in the wet stored logs. In the logstore colony growth was minimal when bark was removed, whereas significant extension of some colonies occurred when lifted bark was bound back into position. In undisturbed logs colony growth appears to occur through extension of the mycelial fans beneath intact bark and radial growth of hyphae into the sapwood along the xylem rays.

In Queensland *R. lineatus* occurs on stumps and logs in rainforests, and has been found as a decay fungus in living ornamental hardwood trees. Herbarium collections indicated that fruiting takes place at least between late December and late April in Queensland. Cultural pairing tests demonstrated that the brown decay zones in the stored logs comprised one or more genetically and spatially distinct mycelia, confirming the establishment of primary colonies by means of basidiospores. It is therefore surmised that logs became colonised from large numbers of spores of *R. lineatus* while being harvested and stored during the summer autumn fruiting period, 1994-95. Further research is needed to better understand the behaviour and growth of *R. lineatus* and to determine the feasibility of sprinkler storage of logs in south east Queensland.

INTRODUCTION

A period of drought throughout much of Queensland resulted in dry conditions in Beerburrum Forest towards the end of 1994. Following two wildfires on September 27 and November 6-7, respectively, an operation was undertaken in state forest stands to salvage approximately 600 thousand m^3 of logs of mainly *P. elliottii* var. *elliottii* Engelm. Of these 400 thousand m^3 were stockpiled under aqueous sprinkler irrigation by mid 1995. Logs stored during the first part of the salvage operation were mostly unstained ("whitewood" logs), but eventually a large proportion of "bluewood" logs stained by *Ophiostoma ips* (Rumb.) Nannf. inoculated into fire-damaged trees by the bark beetle *Ips grandicollis* Eichoff. were also included. In January, 1996, a serious decay problem was discovered in the stored logs and urgent studies were initiated to determine the nature of the causal fungus and if possible to find a means of containing it. This paper summarises research undertaken on the identification, spread, development and growth of the decay fungus at different temperatures and oxygen concentrations in the laboratory and in the stored logs. It also speculates on the occurrence of the decay fungus in the Beerburrum Log Storage Facility and indicates where further information is needed.

MATERIALS AND METHODS

Fresh fruitbodies collected from logs in the Beerburrum Log Storage Facility during February-April, 1996, were studied and compared with dried herbarium specimens and with fruitbodies of decay fungi collected from *Pinus* log debris within several kilometres of the logstore. Occurrence and distribution of *R. lineatus* in the stored logs were assessed in January by teams of two. This survey included an evaluation of the incidence of ambrosia beetle (*Xyleborus perforans* Wolliston) also active in the stored logs (F.R. Wylie, unpublished data). Assessors visually estimated the incidence of logs with fruitbodies in each of approximately 48% of the 197 bays present in the logstore. A more limited follow-up survey of selected bays was undertaken in March by two people after some bays had been opened. The appearance and distribution of decay caused by *R. lineatus* was investigated during the selection and sawing of logs in a milling study, by sectioning logs using a chain saw, and by microscopic and cultural studies in the laboratory.

Laboratory experiments were undertaken to determine significant growth and behavioural properties of *R. lineatus* in order to explain its occurrence in the logstore. These included cultural pairing to determine isolate compatibilities, and growth rate comparisons at different temperatures and under different atmospheric oxygen concentrations. Isolates of *R. lineatus* from logs in the logstore were paired on malt agar and evidence of antagonism between cultures was recorded as colony margins grew together. Fruitbody context isolates of *R. lineatus* from the Beerburrum Log Storage Facility were cultured on malt agar in a multi-range incubator that allowed the simultaneous determination of radial growth rates over a range of different temperatures under aerobic conditions. Isolates were compared from pileate and resupinate fruitbodies, with the pore layer coloured white or orange-pink.

Because wet storage is theoretically designed to protect logs by creating anaerobic conditions within the wood, a study was undertaken to investigate the ability of *R. lineatus* to grow at different concentrations of atmospheric oxygen, and to compare its behaviour with that of a number of decay fungi fruiting in plantations adjacent to the logstore. Isolates of the following species were used in the study: *Rigidoporus lineatus*, *Trametes lactinea* (Berk.) Pat., *Lentinus strigosus* (Schw.) Fr., *Gloeophyllum abietinum*, (Bull.: Fr.) P. Karst., *Tyromyces* sp., and a stock culture doubtfully identified as *Trametes hirsuta* (Wulf.: Fr.) Pil. Cultures freshly isolated from fruitbody context tissues or subcultured from stock collections were grown on malt agar in each of three different oxygen atmospheres: ambient (20% oxygen), microaerophilic (ca. 5%), and trace (< 5%). Requisite atmospheres were produced in growth chambers using commercially supplied gas generator envelopes. Radial growth rates of cultures were compared statistically between species, isolates and oxygen regimes.

Studies were undertaken to investigate the growth of *R. lineatus* in sprinkled logs in the storage facility. In the first study one brown decay colony per log was selected in eight bays in the "whitewood" area. Bark was removed and three or four cores were taken along each log across the apex of the decay zone margin. Sampling was repeated periodically between February and April, 1996 in two slightly different timing series (Series 1 and 2). Cores were coded according to their position and distance from the colony margin at the start of the study. Isolations were attempted by aseptically plating segments of wood from within each core at 3 or 4 points along its length and yields of *R. lineatus* were recorded. In the second study, core samples were taken from logs in three bays without removing the bark. A circular punch was used to cut inspection windows through the bark in order to locate the position of the colony margin. Cores were drilled over the tops of the windows, as before, taking care to minimise bark disturbance. After isolating, cores from the first samplings in both studies were used for measurement of moisture content.

A supplementary growth study was conducted on a number of logs in which the margin of the decay colony was outlined using small round-headed pins before replacing and firmly binding the bark in its original position. This procedure was repeated weekly and measurements recorded of the movement of the margin of the mycelial fans. After four weeks selected logs were sectioned longitudinally and the positions of the associated brown stain and decay were inspected in the laboratory.

RESULTS

Fruitbodies of one fungus, *Rigidoporus lineatus* (Berk.) Ryvarden, predominated on logs stored in the Log Storage Facility. Although collections varied in form and pore surface colour they were microscopically identical and matched published descriptions (Cunningham, 1965; Ryvarden and Johansen, 1980; Corner, 1987) and dried collections held in herbaria QFRI, BRIP and PDD (locations listed in Acknowledgments). Metuloids were frequent in some fruitbodies but absent in others. Cultures from fruitbody context and associated decay were identical, and also matched descriptions of this species (Davidson *et al.*, 1942; Bakshi *et al.*, 1963; Stalpers, 1978). Other basidiomycete decay fungi were occasionally found fruiting on stored logs included *Peniophora* sp., *Poria* sp. and *Schizophyllum commune* Fr. Fruitbodies of the species identified as *Peniophora* sp. were observed on sapwood on the ends of logs in January and were still present in June, 1996.

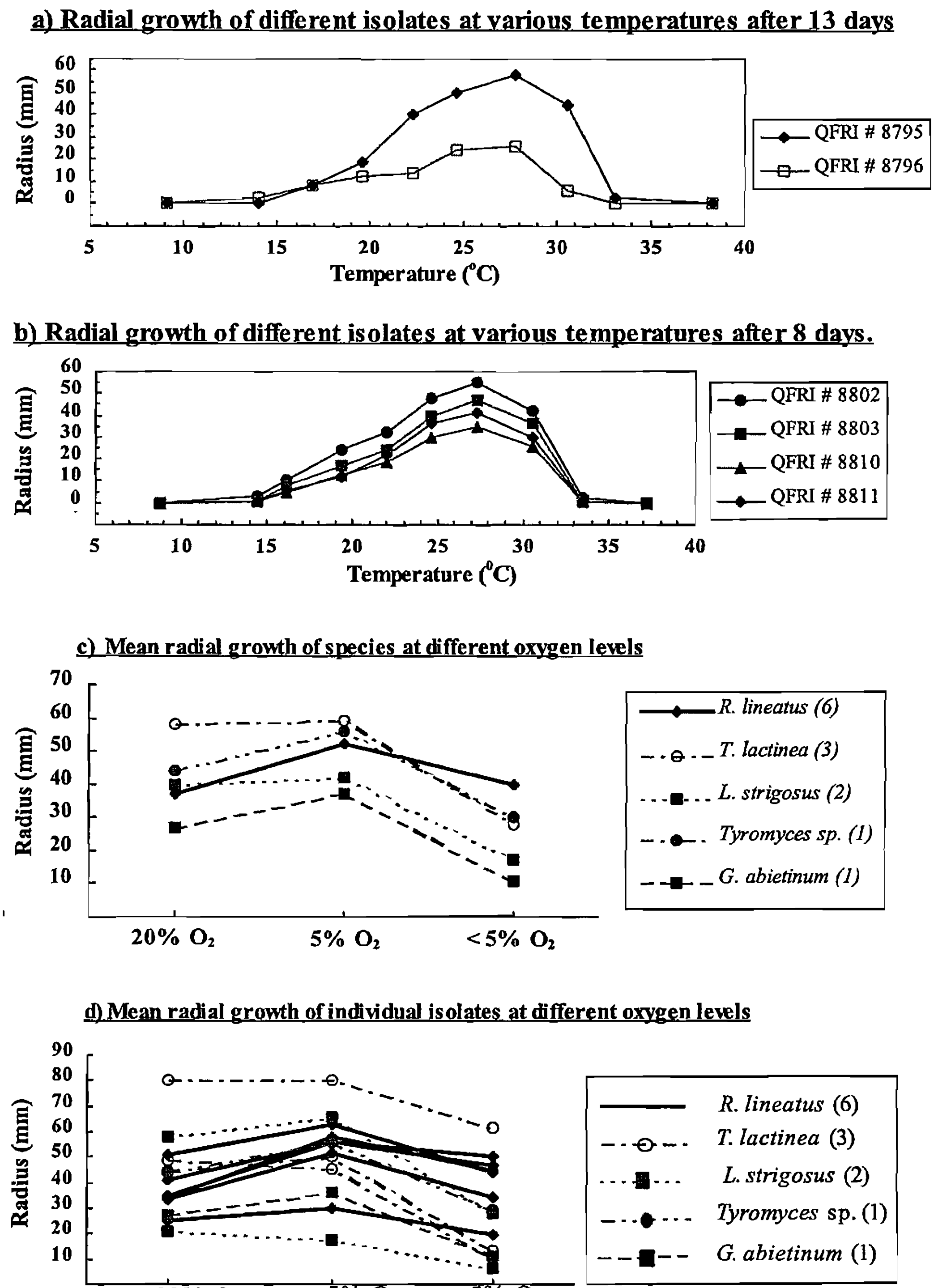

Figure 1: Growth of *Rigidoporus lineatus* isolates in culture: (a) & (b) Temperature profile studies and (c) and (d) Comparisons with other wood decay fungi at different oxygen concentrations.

Table 2. Percentages of cores yielding cultures of *Rigidoporus lineatus*[1]

DATE (1996)	Core Position A: Brown zone (> 20 mm from margin)	B: Brown zone (< 20 mm from margin)	C[2]: White zone (< 20 mm beyond margin)	D: White zone (> 20 mm beyond margin)
(a) With bark removed				
SERIES 1 (25 logs)				
13 Feb.(start)	55 % (29)	27 % (22)	0 % (11) a	0 % (38)
12 March (after 4 weeks[4])	84 % (25)	43 % (21)	19 % (16) ab	3 % (38)[3]
23 April (after 10 weeks[4])	55 % (22)	41 % (17)	35 % (17) ab	0 % (16)
SERIES 2 (10 logs)				
28 February (start)	67 % (9)	55 % (11)	0 % (9) a	0 % (11)
20 March (after 3 weeks)	38 % (8)	46 % (13)	0 % (9) a	- (0)
30 April (after 9 weeks)	100% (12)	100% (6)	50 % (8) b	0 % (4)
(b) With bark retained (11 logs)[5]				
18 April.(start)	71 % (7)	31 % (13)	0 % (2) a	0 % (33) a
28 May (after 6 weeks)	60 % (5)	56 % (9)	40 % (5) a	15 % (26) b

[1]N$^{o.}$ cores in brackets.
[2]Within columns and for each study (with or without bark), values linked by the same letter are not significantly different ($p > 0.05$, Fisher's exact test)
[3]Represents a positive isolation from 1 core of slightly ambiguous location in relation to the margin of the brown zone; not significantly different from other D values in the same column ($p > 0.05$, Fisher's exact test).
[4]Samples from 5 logs after 5,11 weeks, respectively.
[5]Data from 2 trees excluded at 6 weeks due to contamination.

In both coring studies *R. lineatus* was isolated initially only from within the brown zone (A and B cores) in each log series (Table 2.a,b). Four weeks after removing the bark the fungus was isolated immediately beyond the original colony margin (C cores) from only three of the 35 logs, and significant movement into the C core zone was detected only after 9 weeks in the second log series (Table 2.a). There was no significant movement at all more than 20 mm beyond the original margin (D cores) after 9-11 weeks. Cultures appeared to emerge in apparently equal amounts from all positions along the core length. In the second coring study, colonies in three logs with bark retained demonstrated movement of more than 20 mm in six weeks. Values for moisture content were high (95-120%, dry weight basis) in cores from both the brown zone and adjacent white sapwood in both studies.

During the third growth study, mycelial fans grew rapidly in some but not all of the experimental logs beneath bark that had been replaced. Growth appeared greatest where the repositioned bark was most firmly bound. Longitudinal sections indicated that in some logs there was also extension of the brown stain within the sapwood. White aerial mycelium produced at the internal margin after incubation of the sectioned log demonstrated that viable mycelium of *R. lineatus* was present within the newly extended brown zone.

DISCUSSION

Nearly all decay in the Log Storage Facility was caused by *Rigidoporus lineatus*. Identification of this species relies on the presence of metuloids which varied within the fruitbodies and was not as helpful a diagnostic character as indicated in the literature. However, fruitbodies were anatomically identical in all other respects and there can be no doubt about the identification which was corroborated by L. Ryvarden (University of Oslo, Norway) and J.A. Simpson (Research Division, State Forests of New South Wales).

Most collections of *R. lineatus* in Australia are from Queensland where it is common on stumps, logs and sometimes dead wood in living trees, in rainforests and on planted ornamental hardwoods (Cunningham, 1965; Hood *et al.*, 1996). *R. lineatus* has been collected on dead hoop pine trees (*Araucaria cunninghamii* D. Don), but was not previously known on *Pinus* in Queensland, and was not found during the surveys outside the Log Storage Facility.

The first survey in January gave only a limited picture of the true distribution of decay in the logstore because not all colonised logs may have produced fruitbodies, large groups of logs were inaccessible, and the difficulty of assessing whole bays meant that significant bias between observers was a possibility. The follow-up survey in March when some bays had been opened suggested that the assessment in January may have underestimated the incidence of decay. Distribution appeared uneven with pockets of decayed and undecayed logs alternating along bays. Noteworthy were the substantial estimates for the "bluewood" bays, although still generally lower than values assessed for bays in the "whitewood" section. Both surveys provided information on the frequency of logs attacked, but not on the quantity of wood decayed.

The growth studies indicated that colony extension along logs was significant but very slow when bark was removed. On the other hand mycelial fans grew rapidly beneath bark that was fastened back in place, and some colonies expanded within the sapwood following such treatment. In both studies artificial bark disturbance may have affected results. The second coring study in which bark was retained was designed to resolve this ambiguity, but occasional bark movement during drilling may still have induced some unnatural mycelial growth. Results from these studies indicate that colony growth was not prevented by sprinkling, but actual growth rates still remain to be determined. Although values for sapwood moisture content were only approximate because the cores experienced some drying during laboratory processing, the results imply that moisture content was high in both the brown zone and adjacent white sapwood at the time of sampling. Apart from colony extension, the progress of degrade in the stored logs would also depend on the rate of decay and the frequency with which new colonies were established, neither of which was studied. However, there was evidence of secondary colonisation by means of mycelial cords, and new colonies may also have been initiated by means of basidiospores.

The widespread occurrence of discrete colonies indicated that basidiospores were responsible for primary colonisation, possibly invading through newly exposed sapwood at the ends of logs and where bark was dislodged during handling. The cultural pairing experiments confirmed that the mycelia of *R. lineatus* in the brown decay zones from different logs were genetically distinct and therefore derived from different spore parents. Some brown zones were composed of at least two separate mycelial colonies closely associated with one another, and long lines of decay running more than half the length of some logs in the interiors of stacks probably resulted from the meeting of multiple zones.

Collections in herbaria indicated that fruiting of *R. lineatus* occurs in Queensland at least between late December and the end of April. Basidiospores are produced prolifically and appear to be widely dispersed, since *R. lineatus* occurs throughout Queensland in suitable habitats (Cunningham, 1965, Hood *et al*., 1996). This implies that the logs being harvested over the 1994-1995 summer-autumn period were being stored during the sporulation period and exposed to large numbers of basidiospores. The distinctive behaviour of *R. lineatus* at different oxygen concentrations in the laboratory study may explain its wide distribution under the conditions present in the wet-stored logs. Whereas *R. lineatus* is a species apparently able to maintain activity at reduced oxygen concentrations, the other decay fungi were at a competitive disadvantage and were present only in pine debris outside the logstore where oxygen levels were not restrictive. *R. lineatus* has also been reported in wooden pit props in mine tunnels likely to be saturated by contact with moist soil (Thrower and Osborne, 1961), and unlike the other decay fungi tested, it is also found in living trees where moisture content may be substantial.

There are several possible explanations for the initially lower estimates of decay in the "bluewood" area of the logstore. The bluestain fungus *Ophiostoma ips* may have in some way created conditions unfavourable for the establishment of *R. lineatus* at the time when logs were being stored. Alternately, "whitewood" logs were stored during the peak of the natural fruiting period of *R. lineatus* and may have received most of the basidiospore inoculum. Or, finally, colonisation is likely to have been equally substantial on "bluewood" logs, but having occurred later (after ca. February) there was insufficient time (less than a full year) for decay to develop prior to assessment.

Drying commenced early following the Beerburrum fire, and moisture content levels in the outer sapwood in many standing trees had fallen below 110% ten weeks after the second fire (unpublished data). Spores settling on logs during the salvage operation may therefore have colonised the logs before sprinkling had raised wood moisture content to safe levels (Liese, 1984; Gibbs *et al.*, 1996). Sprinkling apparently favoured colonisation by *R. lineatus* over other fungi and did not prevented its development once established. Decay was more advanced and fungal colonies appeared more numerous deeper in the log piles. Although high moisture levels were recorded in the sapwood from logs within the "whitewood" area (T. Copley, K. Harding, D. Gough, unpublished data), it is possible that rewetting to safe levels may have taken longer deeper in the log piles.

Further research is urgently needed for a better understanding of the nature and behaviour of *R. lineatus* and in order to establish the feasibility of successful wet log storage after fires in Queensland. Important aspects needing attention include: the potential for spore colonisation and growth of the fungus at various moisture and oxygen concentrations in logs with and without bark; the effectiveness of different water sprinkling regimes in protecting logs of varying quality from colonisation and decay at different times of the year; a knowledge of the fruiting season, sporulation period and dispersal distances of the fungus; and the ability of *R. lineatus* to colonise trap logs shortly after felling and partial drying. It appears that the use of water sprinkling may not be as straightforward as is sometimes implied. Knowledge is still fundamentally empirical, often sketchy, and not always readily accessible. Many of the principles are still being determined (Hayward, 1981; Gibbs and Webber, 1996). More papers are reporting the occurrence of decay in irrigated logstores, though normally only at a low incidence after several years of storage (Hayward, 1981; Liese, 1984; Peralta *et al.*, 1993; Gibbs and Webber, 1996; Gibbs *et al.*, 1996). A recent example of more substantial sapwood decay caused by a species of *Armillaria* in an irrigated logstore in Germany closely resembled that caused by *R. lineatus* at Beerburrum in growth and behaviour (Schumacher and Grosser, 1995; Gross and Metzler, 1995). Like *R. lineatus*, species of *Armillaria* are found in living trees and have been reported in moist wooden tunnel supports (Farr *et al.*, 1919; Fassatiova *et al.*, 1974). In a similar example, colonies derived from basidiospores of *Armillaria gallica* Marxmüller and Romagnesi also became established in the bark in an irrigated logstore in the United Kingdom (Gibbs *et al.*, 1996). Hyphae failed to penetrate to the sapwood of pine (*Pinus nigra* ssp. *laricio* (Poir.) Maire), but in sycamore logs (*Acer pseudoplatanus* L.) quite extensive decay resulted.

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HEAT STERILISATION OF WATER STORED TIMBER INFECTED WITH THE WHITE ROT DECAY FUNGUS *Rigidoporus lineatus*

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ABSTRACT

The time and temperature combinations lethal to *in vivo* infections of *Rigidoporus lineatus* (Pers.) Ryvarden were investigated in laboratory tests and field trials. Exposure to temperatures of 45°C for 2 hours or 50°C and above for 1 hour killed all infections in wood block samples. Lethal temperatures (>65°C) were achieved in pole timbers during commercial scale field trials after 9 to 10 hours, depending on the heating process. Heat treatment is an effective method for the sterilisation of timber infected by *R. lineatus.*

INTRODUCTION

Following the discovery of extensive fungal infestation of logs in the Beerburrum water store, several potential purchasers expressed interest in the use of heat to sterilise infected material prior to air drying. These purchasers produce posts and shaped, "Beznered" poles for a variety of end uses and, typically, processing involves; selection of logs, de-barking, shaping and air drying. Air drying and outdoor storage prior to preservative treatment can be from 3 to 6 months duration. Brown staining associated with the early stages of infestation by *Rigidoporus lineatus* (Pers.) Ryvarden was considered to have no effect on the use of log storage wood for CCA treated posts and poles, but serious consequences would be expected should the fungus continue to develop to its pocket rot form during the air drying period.

The basidiomycete *Rigidoporus lineatus* was identified as the fungus causing the infection of water stored logs of *Pinus elliotii* Engelm. (Hood, 1996). *R. lineatus* is reported as common and widespread throughout the tropics, infecting living trees and, more significantly, causing decay of wet timbers, most notably in mines, (Ryvarden and Gilbertson, 1994). *R. lineatus* causes a white pocket rot of timber (Pegler and Waterston, 1968) and is regarded as representing a severe decay hazard with recorded dry weight losses of up to; 51.4% in *Eucalyptus fastigata* D. and M in twenty weeks (Thrower and Osborne, 1961) and 43.6% in *P. elliotii* after 12 months (Blumenfeld, 1984) under various experimental conditions. Weight losses to this degree imply considerable strength losses (Wilcox, 1978) and are unacceptable in pole timbers.

Post-harvest, pre-treatment decay is a common cause of degrade of air drying utility pole timbers worldwide (Zabel and Morrell, 1992). Poles extracted from water-storage and undergoing air drying will be at moisture contents suitable for fungal growth for extended periods and are likely to suffer significant decay if the *R. lineatus* infection is not killed prior to drying. The heat-treatment or steaming of poles is commonly used to reduce storage decay and improve preservative treatment of softwood timbers in the USA and New Zealand. Pre-treatment decay is reduced by exposing existing fungal infections to lethal temperatures effectively sterilising the timber (Eaton and Hale, 1993).

Several authors have published work on the survival of basidiomycete fungi at elevated temperatures. Humphrey and Siggers (1933) investigated 56 species of wood decay fungi and found that none would grow above 46°C but give no data on survival. Chidester (1937; 1939) studied the combinations of time and temperature necessary to kill fungi in decayed wood samples. She reported that a temperature of 65.6°C was needed to be maintained in the wood for 75 minutes to kill all the test fungi. The more heat resistant fungi survived 12 hr exposure to 60 °C, 20 hr at 50.5°C, or 24 hr at 50°C. In a study on the temperature tolerance of fungi isolated from wood chip piles, Hulme and Stranks (1975) reported that, under humid conditions, seven of eight basidiomycete decay fungi tested were killed by less than 8 hours exposure to 65°C, the exception being the white rot fungus; *Phanerochaete chrysosporium*. Mizumoto (1951) reported survival of *Lenzitus trabea* under humid conditions for 3 hours at 80°C. It is generally recognised that fungi are more susceptible to exposure to any given temperature at high relative humidity, ie steam treatment, than low humidity. Due to the variable susceptibility of different fungal species and the lack of available data on the temperature tolerance of fungi in the genus *Rigidoporus* the following investigations were undertaken.

MATERIALS AND METHODS

Determination of lethal time and temperature exposure.

Badly infected wood blocks were cut from water stored logs with oven dry moisture contents in the range 125 to 210%. The presence of active white hyphal growth extending from discoloured portions of the wood was used as an indicator of *R. lineatus* infection, this was confirmed by microscopic examination for the presence of acanthophyses, a diagnostic feature (Pegler and Waterston, 1968). Test blocks were heat treated at different temperatures for different periods of time with either steam or dry heat. The various combinations of temperatures and times used in the experiment were 45, 50, 55, 60 and 65 °C for one, two or six hours. Infected blocks were maintained as control samples at ambient temperatures under humid or dry conditions during the high temperature treatments.

For each temperature, 30 test blocks (50 x 50 x 50 mm) were heated in either, the experimental steam kiln at Salisbury Research Sawmill, Brisbane (high humidity exposures) or an electric drying oven (low humidity). Temperatures within the kiln or oven and within representative wood blocks were measured using thermocouples connected to a data logger with a display capability. The start of the exposure time was taken as the point at which the wood attained the target temperature. Ten blocks were removed from the kiln or oven after each exposure time and incubated at 27 °C for up to 30 days. Emergent fungi were identified and any surviving *R. lineatus* infection recorded. Test blocks were retained for periods up to 3 months and regularly reassessed for the presence of surviving *R. lineatus.*

Heat treatment of infected timber prior to air drying.

International quarantine regulations generally require 75 minutes exposure at 65.6 °C for the sterilisation of wood and wood products. Some of the affected poles were intended for the export market and so in order to comply with regulations and ensure thorough sterilisation a target was set of 90 minutes exposure to 66 °C. Two separate investigations were undertaken both designed to best suit the facilities and processes of two potential customers for water stored logs.

The first field trial was designed to sterilise utility poles prior to air drying. The poles were 9.6 metres in length with a butt diameter of 250 to 350 mm. Poles were stacked on bearers in 10 layers, each containing approximately 20 poles with other poles positioned between layers as spacers. The stacks were covered with an insulated tarpaulin. Initially, a 16 hp steam generator was used but later trials were undertaken using a 64 HP steam generator. Thirty thermocouples were positioned inside poles representative of the whole stack and within stack spaces to monitor the air temperature. Thermocouples were fixed in the centre of poles with external silicone sealant to inhibit heat transfer along the wires. Readings were recorded every 15 minutes by data logger. The experiment was repeated several times with both the 16 hp and the 64 hp steam generators to ensure that the target temperature (66 °C) could be exceeded for a sufficient period of time in all the poles throughout the stack. Core samples were removed before and after steaming for assessment of the effectiveness of the method in killing the *R lineatus* infection. The second field trial was undertaken with 200 mm diameter "Beznered" poles heated in stickered bundles in a conventional sawdust fired kiln. The second trial was set up in a similar fashion to the utility pole trial. The aim of these trials was to determine the time of exposure necessary to achieve lethal temperatures with each system and not to devise a drying schedule.

RESULTS.

Determination of lethal time and temperature exposure.

R. lineatus survived in control blocks maintained at ambient temperatures under humid and dry conditions with 82% and 66% successful isolations respectively. Seventy percent of *R. lineatus* infections survived in wood blocks when exposed to 45 °C for one hour under low and high humidity conditions, all other combinations of time and temperature proved lethal. A summary of the results is presented in Table 1.

Table 1. The survival of *in vivo R. lineatus* infections when exposed to various time and temperature combinations at high and low humidities.

Block temperature	Exposure time (hours)	Survival high humidity	low humidity
45 °C	1	7/10	7/10
	2	0	0
	6	0	0
50 °C	1	0	0
	2	0	0
55 °C	1	0	0
	2	*	0
	6	0	*
65 °C	1	0	0
	2	0	0

* results were not available for these tests due to the failure of heating or monitoring equipment.

Heat treatment of infected pole timbers prior to air drying.

It soon became clear that the 16 hp generator did not have sufficient power to heat the stacked poles to the required temperature within a reasonable time. Figure 1(a) presents data recorded during a typical trial run and shows that even after 20 hours of steaming the minimum temperature recorded within the poles was 55°C, the mean temperature of all the experimental poles was approximately 60°C. Despite the failure to achieve the target time/temperature combination in this run no *R. lineatus* infection was detected after steaming. After several runs with the 16 hp system the steam generator was replaced with a 64 hp system and Figure 1(b) presents data from a typical successful run using this generator. The poles attained a minimum temperature of 66°C within 11 hours with the mean temperature being 72°C. No *R. lineatus* infection was detected after steaming. The rapid fall off in air temperature was due to the opening up of the tarpaulin and the ingress of cold air. Figure 1(c) presents data gathered during an unsuccessful run using the 64hp generator. During this trial the minimum temperature reached was only 28°C with a mean of 38°C. Isolations from this material suggested that approximately 90% of the original infections remained active after steaming. The failure of this treatment was due to repeated mechanical breakdown and inefficient running of the steam generator as indicated by the irregular and slow increase in air temperature. Figure 1(d) presents data from a representative heat treatment of "Beznered" poles in a commercial kiln. The target temperature was reached in 9 hours. The mean temperature of poles at this time was 69°C with a minimum recorded value of 66°C. No *R. lineatus* infection survived this treatment. The regular sawtooth pattern of the kiln temperature was caused by the switching of the thermostatic control mechanism.

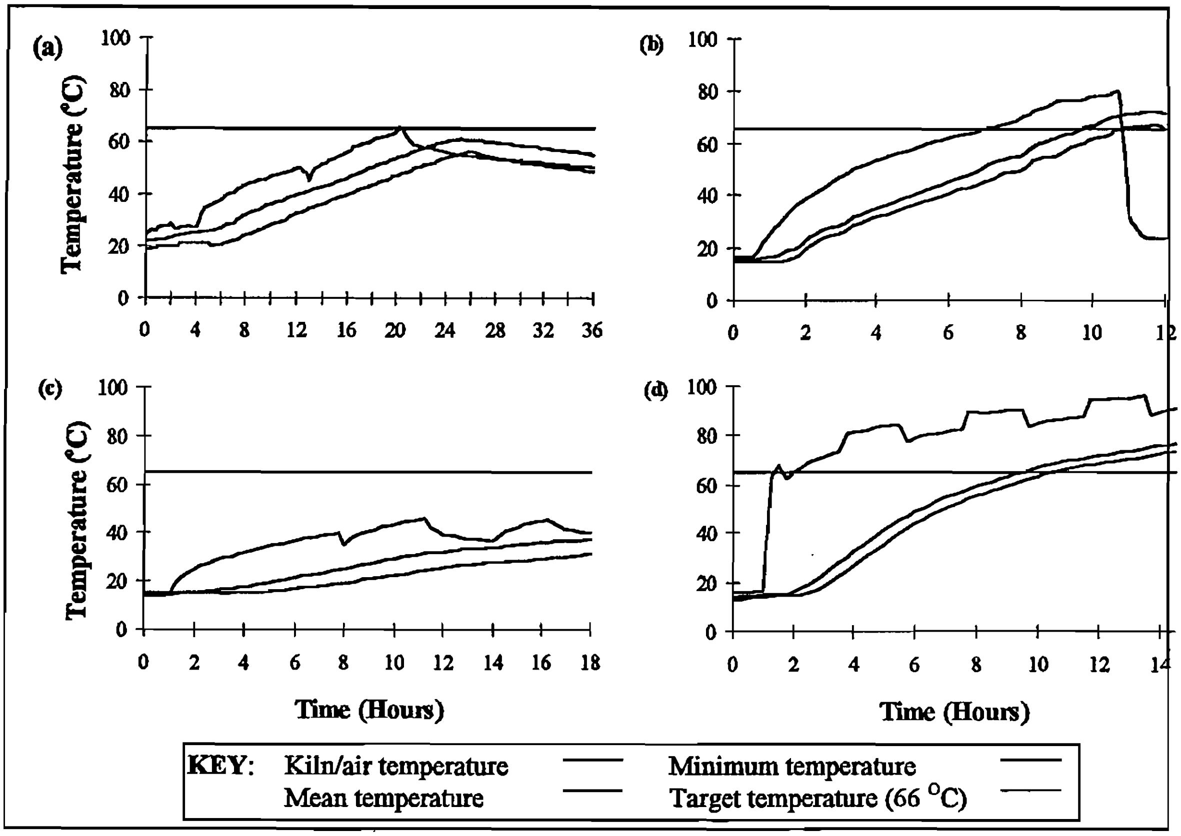

Figure 1. Time and temperature profiles within poles and pole stacks during heat sterilisation treatment of; utility pole timbers steamed (a) with a 16hp generator, (b) with a 64hp generator, (c) unsuccessfully with a 64hp generator and (d) "Beznered" poles successfully heated in a conventional drying kiln.

DISCUSSION AND CONCLUSIONS

In vivo infections by *Rigidoporus lineatus* are readily killed by 2 hours exposure to temperatures of 45°C or 1 hours exposure to 50°C and above. This was shown to be true in both laboratory and field investigations and concurs with experimental data of Hood (1996) who found that *in vitro* cultures of several isolates of *R. lineatus* would not grow at temperatures greater than 38°C. It is concluded therefore that heat treatment is a suitable method for sterilisation of infected timbers prior to air drying. The field trials described here showed that it is possible to attain temperatures in excess of 66°C within utility poles in 10 hours using the temporary and portable system of a 64hp steam generator with insulating tarpaulin and within 9 hours with 200mm diameter rounds heated within a conventional drying kiln. However, both systems were prone to occasional failure and incomplete heat treatment did not kill all infections. Regular monitoring of internal pole temperatures is necessary to ensure successful sterilisation and prevent excessive heating that can lead to strength losses (Wilkinson, 1979) and will incur unnecessary fuel costs.

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MANAGING ATTACK BY BARK AND AMBROSIA BEETLES (COLEOPTERA: SCOLYTIDAE) IN FIRE-DAMAGED *PINUS* PLANTATIONS AND SALVAGED LOGS IN SOUTH-EAST QUEENSLAND

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ABSTRACT

In late 1994, bushfires in the Beerburrum area north of Brisbane damaged 8688 hectares of pine plantations (mostly *Pinus elliottii, P. caribaea* and *P. taeda*). In the 4712 hectares of government-owned plantations affected, large scale salvage operations were commenced quickly in order to minimise damage by the established exotic bark beetle *Ips grandicollis* Eichhoff and associated sapstaining fungi. The bark beetle began attacking fire-damaged trees 6 weeks after the fire and was significant in most areas at 10 weeks. Sapstain carried by *I. grandicollis* became significant at the completion of a life cycle of the insect (about 4 weeks in summer). Losses caused by *I. grandicollis* and sapstain following the fire were estimated at several million dollars Australian, mostly in privately-owned plantations where salvage was delayed for several months.

Salvaged timber was stored on a 49 hectare site at Beerburrum under water spray to inhibit degrade of logs by insects and fungi. Serious attack of the logs by the ambrosia beetles *Xyleborus perforans* (Wollaston) and *Xyleborus ferrugineus* (Fabricius) occurred one year after the storage commenced, and a high incidence of the decay fungus *Rigidoporus lineatus* (Pers.) Ryvarden was also detected in stored logs at that time. The circumstances associated with the insect attack and management options are discussed in this paper.

INTRODUCTION

In late September and again in early November 1994, bushfires in the Beerburrum region north of Brisbane swept through native forests and plantations of exotic pine (mainly *Pinus elliottii, P. caribaea* and *P. taeda*). A total plantation area of 8688 hectares was affected, of which 4712 hectares were government-owned. In these latter plantations, large-scale salvage operations commenced quickly to harvest damaged timber. Operations were given impetus by the presence in the region of an exotic bark beetle, *Ips grandicollis* Eichhoff, which attacks damaged *Pinus* spp. trees and logs. The insect carries a fungus, *Ophiostoma ips* (Rumb. Nannif.), which can kill trees and stain the wood, reducing its value (Neumann 1987). There was also concern about possible degrade of standing trees and logs by other species of sapstain and decay fungi and by ambrosia beetles, particularly the island pinhole borer *Xyleborus perforans* (Wollaston). This borer had attacked burnt *Pinus* spp. trees at Toolara (120 km north of Beerburrum), approximately six months after a fire which occurred in September 1992, resulting in the rejection of some salvaged timber destined for use as poles.

Following the Beerburrum fires, the incidence of insect and fungal attack in affected government-owned plantations was monitored in order to provide forest managers with information on when and where to salvage in advance of serious degrade by these organisms. The total volume of timber in those damaged stands was estimated at 800 000 m^3. Of this, approximately 600 000 m^3 of log timber was ultimately salvaged during the period December 1994 to July 1995.

The majority was classed as 'whitewood' (that is, of sawlog and plylog quality and free of serious degrade), but some of the material harvested towards the end of the salvage period was classed as 'bluewood' (that is, with degrade caused by insects and sapstain). About 200 000 m^3 of the salvaged material was taken direct to mills for processing and the remainder went into storage at a specially-prepared 49 hectare site at Beerburrum. The logs were kept under waterspray applied at a rate of about 150 mm / day to inhibit degrade by insects and fungi.

Observations resulting from various surveys and studies carried out post-fire relating to insect attack in damaged standing trees and in stored logs are reported in this paper. Strategies for the future management of such problems are discussed.

BACKGROUND ON *IPS GRANDICOLLIS* IN QUEENSLAND AND RELEVANT BIOLOGY

The fivespined bark beetle *Ips grandicollis* is native to north America and was accidentally introduced into South Australia in 1943 and into Western Australia in 1952 via importation of unbarked pine logs from the United States (Morgan 1967). It was found in Victoria and Queensland in 1982 and New South Wales in 1983 (Wylie and Peters 1987, Eldridge and Simpson 1987). While it disperses naturally by flight, its spread has been assisted by movement of logs and timber with bark attached and of bark chip. It is widely established in exotic pine plantations in south-east Queensland, where a quarantine on northward movement of susceptible material has been in force since 1982, and it has just recently (November 1994) been found in the Byfield plantations in central Queensland. Natural enemies of *I. grandicollis* from the United States have been released in Queensland plantations to assist with the management of this insect, and two species of its wasp parasitoids, *Roptrocerus xylophagorum* (Ratzeburg) and *Dendrosoter sulcatus* (Muesbeck), are now well established.

To date, *I. grandicollis* has mainly been a secondary pest in Queensland, attacking recently felled trees and logging debris, and standing trees damaged by lightning, wind, fire or drought. There have been only a few cases of attack on apparently healthy trees. This is in contrast to the situation in Victoria and South Australia where primary attack affecting large numbers of healthy trees has been recorded on several occasions (usually adjacent to clearfell areas with considerable debris containing high *I. grandicollis* populations) (Neumann 1987).

The life cycle of *Ips* in Queensland is about four weeks in summer extending to approximately 10 weeks in winter. Early external symptoms of *Ips* attack are small quantities of dry, resin-free, reddish-brown borer dust around scattered entrance holes in the bark of standing trees or pine material on the ground. The frass contains an aggregating pheromone produced by the male which attracts females and males to the tree or log. The adults and larvae tunnel in the cambial region and engrave the surface of the wood. The distinctive tunnel pattern and the appearance of the frass, are features that were used to identify *Ips* infestations during the field surveys. Populations of *Ips* produced from attacked material can be high (200-400 adults/ 900 cm^2) and after a generation is completed the bark will appear 'peppered' with emergence holes. In the laboratory, adults have continued to emerge from infested billets for up to 7.5 months after felling and collection.

MONITORING FOR INSECT ATTACK IN STANDING TREES

- **methodology**

Monitoring was conducted using fixed plots as well as numerous random transects and point sampling throughout the fire-damaged areas. The aim was both to assist managers in decision-making during the salvage and to provide predictive data for any future fire events.

Four weeks after the November fires, six research plots each of 60 trees were established in damaged *P. elliottii* plantations. There were two plots in each of three tree-age salvage categories *viz.* trees more than 20 years old (Plots 1,2); 16-20 years (Plots 3,4); 10-15 years (Plots 5,6). Plots were dispersed throughout the area damaged by the November fires. Each plot contained trees with crown scorch ranging from light to totally burnt. These were grouped into three crown scorch categories *viz.*
0 = burnt, no green foliage
1 = moderate to severe, 1-2 whorls of green foliage present
2 = light to moderate, more than 2 whorls of green foliage present.

Several additional trees were included with the plots to allow for destructive sampling (jointly with forest pathology staff) to check on sapstain development and its association with insect attack. All trees in each plot were inspected visually for insect damage at fortnightly intervals until 22 weeks after the fire and thereafter at monthly intervals for one year. At monthly intervals for 6 months, three trees in each plot (one in each of the crown scorch categories) were felled and the extent of any sapstain, decay and insect attack in and along the stem was assessed and recorded (details are provided in Hood and Ramsden 1996).

- **progress of *Ips* infestation**

Results for the 22 week period following the fire for five plots (Plot 2 was inadvertently logged before attack occurred) are shown in Figure 1. The first *Ips* attack recorded in the plots was in Plot 5, six weeks after the fire (four trees infested). The incidence of attack in that plot had exceeded 10% of trees by 8 weeks. This was a level arbitrarily chosen by the salvage team as being of commercial significance and requiring immediate harvesting of the plantation compartment affected. Incidence had exceeded this level in the other plots by 10 weeks. By 12 weeks, 100% of trees in Plot 5 were infested, and incidence in all the other plots except Plot 6 approached this level by 20 weeks. The rate of infestation for most plots was rapid in the first few weeks following initial attack and had begun to plateau at about 16 weeks. One year after the fire, 80% of trees in Plot 6 had been infested.

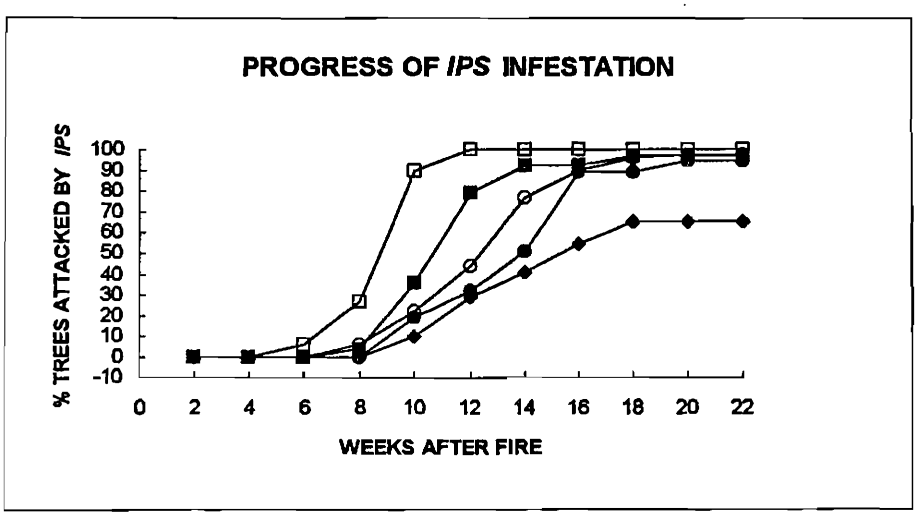

Figure 1: Progress of *Ips grandicollis* infestation in Plots 1 (●), 3 (■), 4 (○), 5 (□) and 6 (◆) with time

- **Ips attack in relation to fire scorch category**

The percentages of trees that had been attacked by *Ips* at 22 weeks after fire in each of the three fire scorch categories for each plot is shown in Figure 2. All categories were severely attacked, category 2 being slightly less affected than 0 and 1. Several of the trees in categories 1 and 2 which were infested with *Ips* a few months after fire retained their green crown for several months after attack but eventually died.

Thus, the degree of crown scorch as assessed four weeks after fire was not a reliable guide to the intensity of fire damage and to the likelihood of attack by *Ips*. That finding was supported by data obtained from the general surveys in which many trees, apparently only slightly affected by fire and still with a full green crown, were attacked by *Ips* although trees of similar age and crown appearance in adjacent unburnt stands suffered no attack. Reasons for this probably relate to localised occurrences of a slower but more intense burn, such as may occur at night, in areas with considerable fuel load on the ground resulting in severe stem burn but no crown damage.

This had considerable relevance for the salvage program because it was expected that trees with more than four green whorls remaining after fire would survive, and it was not intended that such stands would be harvested. Trees that are successfully attacked by *Ips* will eventually succumb, and several such affected stands with full green crowns which were left unharvested died in the spring and summer following the fire.

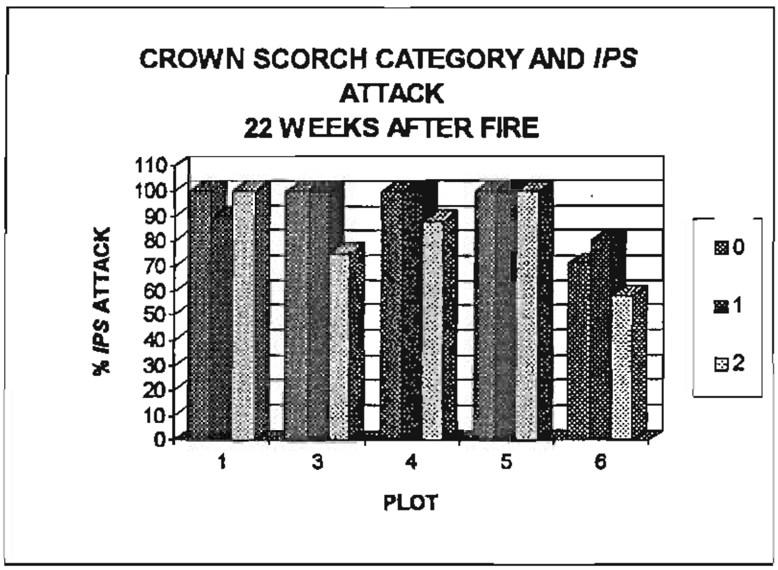

Figure 2: Variation of *Ips grandicollis* infestation with crown scorch category (0, 1 and 2) 22 weeks after the fire

- **association of *Ips* and sapstain**

As reported by Hood and Ramsden (1996), destructive sampling showed that all occurrences of sapstain in the wood of fire-damaged trees were associated with *Ips* infestations. Serious sapstain degrade of the wood began to occur about 4-5 weeks after attack by *Ips*, that is at the completion of a life cycle of the insect in summer.

- **observations from the broadscale surveys**

Numerous transects and spot checks were made in a wide range of fire-damaged plantation compartments throughout the period of the salvage in order to assess their *Ips* status and to assist with decision-making on the timing of harvesting. While emphasis in the salvage was placed on harvesting the high-value, larger-diameter timber first, any areas where transects indicated an incidence of *Ips* infestation greater than 10% of trees were accorded priority. One trend which emerged from these surveys, and which warrants further investigation, is a possible link between the timing of attack by *Ips* in a fire-damaged compartment and the previous logging history of the area. At identical sample times, compartments in areas where thinning or other harvesting operations had taken place within several months prior to the fires, seemed to have a higher incidence of infestation than had comparable compartments in areas which were unthinned or where harvesting operations had taken place prior to 1994. Logging debris in the blocks may harbour *Ips* for up to 8 months. Some of this material is likely to have survived the fire (because a thorough burning is required to destroy infestations) and could have provided a reservoir of the pest to initiate attacks. Other sources of infestation can come from drought-stressed or lightning-struck trees.

All species of *Pinus* damaged by fire (*P. elliottii* var. *elliottii*, *P. caribaea* var. *hondurensis*, *P. caribaea* var. *caribaea* and *P. taeda*) were attacked by *Ips* and appeared to be equally susceptible.

- **other insects**

The island pinhole borer *Xyleborus perforans* was first noticed in standing trees eight weeks after fire and was most common in trees which had been severely burnt. It did not become a serious problem during the six month salvage period, but heavy infestations occurred in trees that were left unharvested.

Termite galleries (*Coptotermes* sp.) were first noticed on the stems of some burnt trees at about 12 weeks after fire but did not cause any significant damage during the salvage period. Infestations of pine bark weevil *Aesiotes notabilis* Pascoe also occurred in some burnt stems.

INSECT ATTACK IN STORED LOGS

- **storage conditions**

Approximately 400 000 m^3 of log timber was placed under water spray at Beerburrum to protect against new attack by insects and fungi (particularly in the case of the unattacked whitewood logs) and to eliminate or arrest the progress of any existing attack (for example, in the bluewood logs). The logs were arranged at the site in 196 stacks ('bays'), each about 150 m long and 4 m high. The layout of the stacks is shown in Figure 3. Lines of water sprinklers were positioned over the top and along the sides of stacks as required to provide good spray coverage. Water was pumped from a dam constructed on the site and was recirculated. The dam was initially filled, and topped up in dry periods, from a nearby tidal creek, reaching a peak salt level of approximately one-third that of seawater. The level of daily watering considered necessary for protection was determined following literature search and extensive consultation. A 24-hour watering regime was employed delivering approximately 150 mm water per day onto the stacks. This regime was later altered in November 1995, in order to reduce pump maintenance and electricity costs, to watering during daylight hours unless conditions were windy or humidity was low. A trial conducted in two bays to test this new regime had shown that the moisture content of logs and percentage moisture saturation had not altered, and subsequent monitoring in these bays confirmed that result.

- **experiments with logs removed from storage**

In addition to general surveillance for insect attack in the stored logs, several experiments were conducted to determine

a) whether the logs remained attractive to borers after several months under water storage,
b) if attractive, how quickly borer attack would occur,
c) whether intermittent watering would prevent or control attack.

In one trial in October 1995, 5 logs each 5.1 m long were taken from each of four different bays (*viz.* early salvage whitewood, late salvage whitewood, early salvage bluewood, late salvage bluewood) and placed on skids together with 5 controls of similar length cut from freshly felled trees. The logs had been under water storage for periods ranging from 5 to 10 months For each log, the percentage surface area with bark still intact was recorded. It ranged from 80-97% for stored logs and 98-100% for the controls. The percentage moisture saturation of the logs at the start of the experiment was also assessed. It ranged from 92-98% for the whitewood logs, 71-97% for the bluewood logs and 71-90% for the controls. The number of insect attacks and species responsible were recorded weekly.

Ips attacked the logs within a few days, and at the first count all logs had been attacked. Bluewood logs had an average of 37 attacks per log, whitewood logs an average of 10 attacks and controls an average of 6 attacks. After two weeks, bluewood logs averaged 200 attacks per log , whitewood logs averaged 130 attacks and the controls 12 attacks. At three weeks, both bluewood and whitewood logs had several hundred attacks per log and the controls 14. Most infestation was feeding attack but some breeding attack and subsequent emergence occurred indicating that the logs were suitable for colonisation. While there were many thousands of *Ips* attacks on these logs, there were only two attacks by ambrosia beetles (*X. perforans*) on one log 2 weeks after the start of the trial.

Another study in November 1995, on the drying rates of logs removed from stacks, produced similar results with regard to attack by *Ips* and ambrosia beetles. *Ips* attack was noted on the first day after log removal and increased rapidly thereafter on all logs with bark attached. The only *Xyleborus* attack recorded during the study occurred on one log (moisture content approximately 65%), two weeks after commencement of the trial.

In a further experiment, 10 billets infested by *Ips* were collected from nearby salvage areas. Five were placed in a stack under water spray and five were left in the open as controls. Each week, one treatment billet and one control were destructively sampled to check on any insect mortality. At the first sampling, all stages of *Ips* in the billet taken from the watered stack were dead while *Ips* in the control remained alive. Throughout the experiment, no live *Ips* were found in watered billets but *Ips* in the controls were active.

- **discovery of attack in stored logs and initial surveys**

Attack by ambrosia beetles (*Xyleborus* spp.) was detected by site staff on 24 January 1996 in a bluewood bay during loading operations, and was subsequently found at several other locations within the facility. Intensive surveys were immediately commenced, and the percentage of infested logs in each stack was recorded. The distribution of attack within the stack and its position on individual logs was also noted (*viz.* whether on upper or lower surfaces of logs, in dry or wet patches, in exposed or sheltered sites). The incidence of attack is shown in Figure 3, categorised into three levels of damage *viz.* 0-2% of logs infested, 3-10% infested, more than 10% infested.

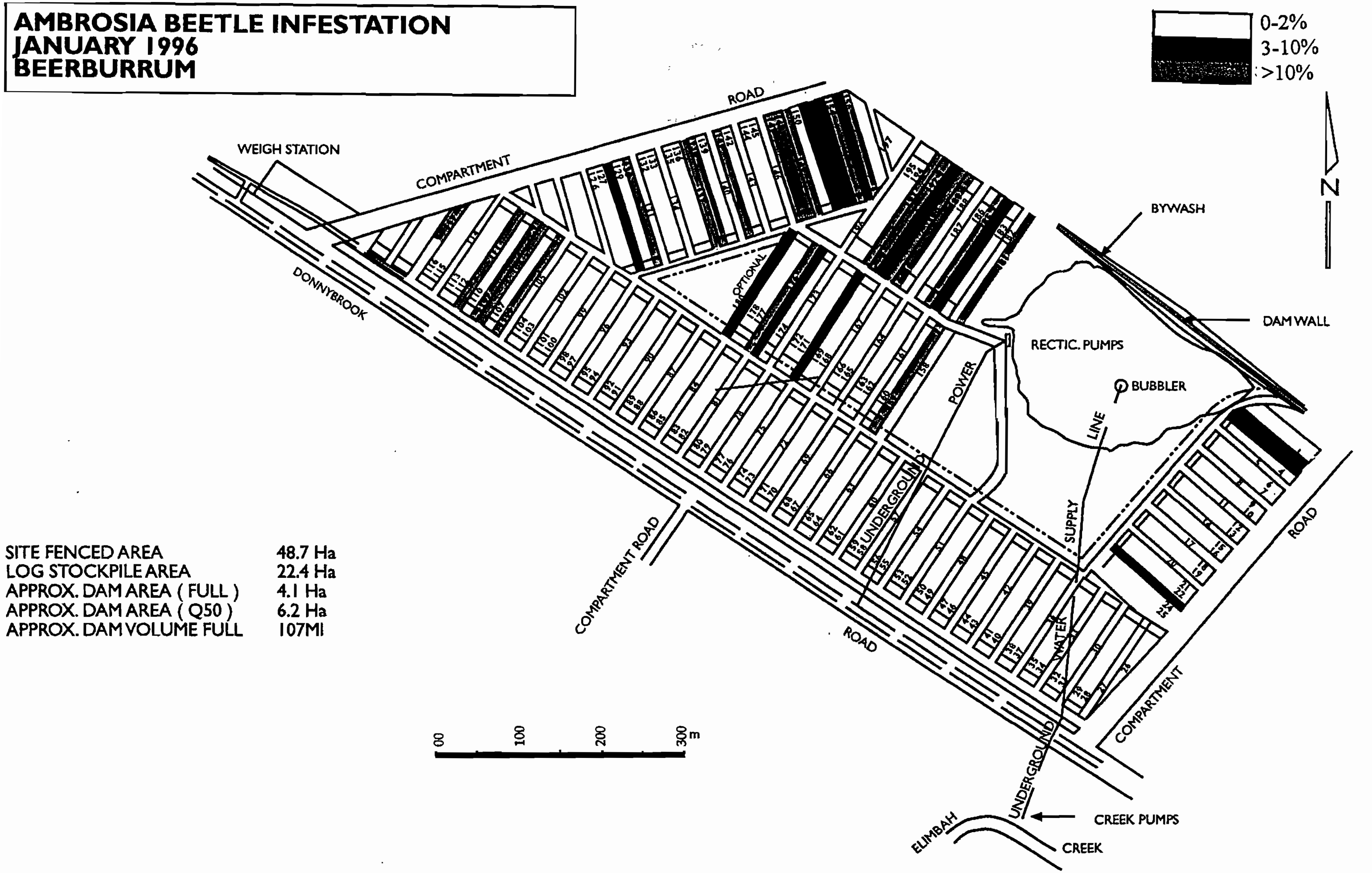

FIGURE 3. Site map of Beerburrum Log Storage Facility showing position of log stacks and incidence of ambrosia beetle infestation.

The insects were present in less than 1% of whitewood logs (the bulk of the resource) and in about 6% of bluewood logs. In almost all cases, attack was occurring in dry patches on the logs, usually on the underside of overhangs or in 'caves' in the stack where water did not appear to be reaching. Attack mostly seemed to be on the ends of the logs but in some cases extended to the centre of the stack. The absence of free-flowing surface water seemed to be a key factor in the attack. Infestation was very rarely found on the exposed parts of stacks, and was usually worst in 'rain shadows'.

Sampling of the wood revealed a preponderance of adult beetles and comparatively few larvae, these being very young. This, coupled with evidence from site staff, indicates that the attack was detected within about a week of its occurrence. One particular stack, Bay 156, had been carefully inspected by Beerburrum staff for sale of wood on 12 January and there was no sign at all of infestation. Twelve days later this was the bay which had the most severe infestation of those surveyed.

Two species of *Xyleborus* were identified from sampled wood, *X. perforans* and *X. ferrugineus* (Fabricius). Both are very similar in appearance and habits. The beetles would have originated from debris throughout the fire-damaged areas. The life cycle of *X. perforans* in Queensland is usually of 2-3 months duration but according to Browne (1961) may be completed in three weeks under optimum conditions. The occurrence of widespread attack in the stored logs in January 1996 coincided with a period of record high temperatures and humidities for the area. This may have stimulated beetle activity, promoted drying of the stacks and accelerated life cycles of these insects.

- **managing the problem and monitoring for new attack**

Following the discovery of ambrosia beetle attack in stored logs, the 24-hour watering regime was immediately reinstated, based on the strong possibility that the reduced watering since November 1995 had contributed to the problem. The findings of the initial surveys supported this approach.

To examine the effects of the increased watering on existing infestations and to check for the occurrence of new attacks, monitoring points were quickly established at 28 locations throughout the facility in the three main categories of attack severity that had been defined in the surveys. A range of sites in stacks was chosen, generally log ends in sheltered or partially exposed situations, some with free-flowing water and some dry. Sampling was stratified according to the severity of infestation. At some of the heavily infested sites, on each of several attacked logs a section was partitioned off with tape, and coloured mapping pins were used to mark the position of borer holes. Nearby apparently-comparable logs without attack were also flagged with tape. At sites where infestation was more dispersed, scattered pairs of attacked and unattacked logs were marked with tape and pins. At sites with very low levels of infestation, sections extending for several metres along the side of the stack were inspected, and just the infested logs marked with tape. Some whole stacks which were found to be uninfested in the initial surveys were also monitored. Inspections were made at intervals of 2-3 days for the first several weeks, thereafter weekly and then fortnightly. Any new attacks were recorded and marked with pins or tapes as appropriate. At the monitoring points, observations were made concerning the condition of the logs (for example, whether surfaces were dry or with free-flowing water) and on the presence or absence of fresh frass around marked holes.

It was found that no new attack was occurring on log surfaces which had a film of free-flowing water, and that restoration of the film over surfaces with existing attack resulted in the cessation of insect activity, generally within a few weeks. To confirm this, infested logs were taken from a comparatively dry section of a stack and placed in exposed positions where they received better sprinkler coverage. Destructive sampling of these logs after three weeks, when frass production seemed to have ceased, verified the death of all stages of *Xyleborus* in the tunnels, while at the same time insect activity continued in the dry section. Monitoring showed that not all parts of stacks were fully rewetting, following restoration of the 24-hour watering regime, and new attack was still occurring in drier patches. Often, dry patches developed because of sprinkler failure, low water pressure towards the ends of long watering lines at distance from the pumps, and windy conditions. The situation was rectified by repair and redeployment of sprinklers, adding new watering lines and boosting pressure with additional pumps.

Moisture content sampling was carried out on infested and uninfested logs in dry spots and on adjacent wet logs, from 3 stacks in each of the 3 categories of infestation delineated in the survey. The percentage moisture saturation of the outer sapwood of 'dry' infested logs was very little different from that of the uninfested logs (means for wet and dry logs were 92% and 91% respectively). No relationship was found between moisture content of the sapwood and heartwood of the logs and intensity of ambrosia beetle attack. Such finding, together with the results of the other trials, surveys and monitoring, showed that it was a lack of free-flowing surface water rather than a lowering of the moisture content of the logs which allowed ambrosia beetle attack to occur.

Trials to compare the effects on infestations of spraying with salt water or with fresh water showed no difference between the two but the increased watering itself resulted in the cessation of activity after two weeks.

Trapping was conducted to monitor the activity of adult ambrosia beetle populations at the storage site over time. Sticky traps were unsuccessful. Modification of the Norwegian-type trap used in Queensland and some other Australian States for the monitoring of *I. grandicollis* populations (see Newman 1987) gave better results. Ethyl alcohol was used in the traps both to attract and to preserve beetles. In March, the numbers of adults collected in each trap per fortnight averaged 117, in April 233, in May 48, in June 19 and in July nil. The highest fortnightly count in a single trap was 336 beetles in mid April. Two species were captured in the traps, *X. perforans* and *X. ferrugineus*, the latter being between two and five times more numerous than *X. perforans*.

Sporadic low level attack by ambrosia beetles continued throughout autumn, always on dry sections of stacks.

OUTCOME AND DISCUSSION

The field salvage phase within fire-damaged government plantations was successful, with almost 75% of the affected resource harvested ahead of serious degrade by insects and fungi. The total losses due to *I. grandicollis* and associated sapstain in damaged stands was estimated at several million dollars Australian, the majority of this in private plantations where salvage had been delayed for several months. The storage phase was less successful. Although the outbreak of ambrosia beetles in stored logs after one year affected only a small proportion of the resource and was able to be managed, infestation by the decay fungus *Rigidoporus lineatus* was widespread and unmanageable. Efforts are being made to sell and process the material as quickly as possible.

This salvage operation was the largest that has been undertaken in Queensland and was the first time that an attempt has been made to store large volumes of pine log timber under water spray for a long period in subtropical Australia. The information obtained during the operation concerning insect and fungal degrade will have a bearing on the manner in which future salvage is managed here. Some of the more important points are discussed below.

Salvage

- *Ips grandicollis* began attacking fire damaged trees six weeks after the fire and was significant in most areas at 10 weeks. Sapstain degrade associated with the beetle became significant 4-5 weeks later. Thus future salvage operations following fire will need to be completed within about three months to avoid serious degrade. This is similar to the situation reported by Wylie and Shanahan (1973) in Papua New Guinea, but very different to the situation in temperate Australia where degrade usually occurs less rapidly (French and Keirle 1969). Following fires in *Pinus* spp. plantations in South Australia in 1984, *I. grandicollis* and sapstain were not a problem (Thomas 1986). However, there the fires were followed by a wet, cold period which inhibited the insect's activity and there was very little non-insect transmission of sapstain fungi.
- The degree of crown scorch as assessed four weeks after fire was not a reliable guide to the intensity of fire damage sustained by trees and to the likelihood of attack by *Ips*. A better method of assessing the likely degree of damage is required incorporating factors such as the fuel load on the ground prior to fire and speed of the burn.
- If a link exists between the previous logging history of a plantation area and the timing of attack by *I. grandicollis* following fire, as indicated by the surveys, then compartments in areas that had been thinned or clearfelled within eight months prior to the fire could be targeted for early salvage.
- Trees which are successfully infested by *I. grandicollis* will eventually die, regardless of the apparent health of their crown, although degrade is slower to develop in green-topped trees (Hood and Ramsden 1996). Such infested stands will need to be included in salvage plans.
- No primary attack by *I. grandicollis* occurred on unburnt trees adjacent to the salvage areas despite the presence of large populations in debris and burnt standing trees. This is surprising considering the experiences in Victoria and South Australia where primary attack has occurred adjacent to clearfell areas (Neumann 1987). Contingency plans in Queensland were for the use of chopper rollers on the slash to reduce breeding sites.

Log storage

- Ambrosia beetle attack on the stored logs after one year was the direct result of the loss of the protective water film over the surface of some logs. The loss of this film both removes a physical barrier to the insects and also allows ethanol (a product of fermentation) to escape which acts as an attractant to the beetles (Elliott *et al.* 1983, Moeck 1970). The loss of the film was certainly associated with the reduced watering regime as attested by the improved situation when full watering was restored. A similar experience with intermittent watering has been reported from the United States, although at less than half the watering rate employed in Queensland (Syme and Saucier 1995). In New Zealand, attack by the ambrosia beetle *Platypus apicalis* White occurred in stored logs after 2-3 years (Milligan 1982) but this event was associated with a failure of the watering system (N.C. Clifton, pers. comm.). Observations in Queensland suggest that the development of dry patches, and consequently of ambrosia beetle attack, would have occurred in time as a result of the settling of the stacks, the filling of crevices with debris from decomposing bark, and the proliferation of algal growth. This would have blocked the free passage of water and may account in part for the slow rewetting of the stacks following restoration of full watering. Webber (1990) outlines the need for careful construction of the log stack to prevent the formation of "eaves" which may prevent water from reaching the logs below.

Interpretation and application of the revised, generalized, natural durability ratings

The revised durability ratings as determined here relate only to mature trees. For information on differences between mature and regrowth trees of some of the same species, see another paper at this conference (Johnson *et al.* 1996b). Information in this paper cannot be used to make predictions of ratings for mature timber of species not included in this test. We accept that many of the timbers listed here are not now commercially available, highlighting one of the difficulties associated with long-term testing and indicating the need for proven reliable accelerated protocols for use in future evaluations. However, those protocols must be based on long-term field data, **especially for the most durable species**, before being considered acceptable.

For all timbers, sapwood that has not been preservative-treated should be regarded as non-durable. Also the inner heartwood - the heartwood nearest the pith - generally has lower durability than the outer heartwood selected for this evaluation.

The generalized durability classification provides two rating values, one against decay, and the other against decay plus termites. The comparative benefit of this classification is achieved at the expense of two other important aspects. Firstly, information on the variability of timber performance is not readily apparent because the lower rating of a range of variation is used. However, the hazard-based classification (Thornton *et al.* 1996) will address the issue of variability to some extent at least. Secondly, the generalized ratings now given, and applicable throughout much of Australia can only be related to each durability class in broad ranges of median specimen lives. The main value of the ratings is to allow timber-to-timber comparisons to be made, with respect to decay only and decay plus termite resistance.

While the new CSIRO durability ratings against decay alone may at first glance be considered to be potentially very useful, some caution in their application is warranted. Where there is uncertainty as to whether termites will continue to be absent from an area over the coming years, it may be wise to exert a preference for usage of the ratings against decay in the presence of termites.

It is worth reminding the reader that the durability of timbers in ground as given in this revision (Table 3) may not provide a useful indication of expected relative durabilities when used in an above-ground situation. Evaluation of above-ground natural durability of commercial Australian timbers is currently being undertaken in a test that was installed in 1987 by Queensland Department of Primary Industry (Forestry).

CONCLUSION

The natural durability ratings given in Table 3 for decay and for decay in the presence of termites are now recommended by the authors as replacements for the earlier CSIRO tentative durability ratings.

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Hazard-based natural durability ratings and mean rates of biodeterioration proposed for use in the reliability-based durability design method

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SUMMARY

Two different forms of natural durability data are offered for consideration by the engineer in the concept of reliability-based durability design. Both deal with a range of combinations of hazard levels, in-ground, from decay and termites. One is mean rate of deterioration and the other is natural durability rating. Both were derived independently from the median specimen life data obtained from five field test sites and from accelerated testing with decay and termites. The resource in all cases is the outer heartwood from mature trees of 77 timber species.

INTRODUCTION

Another paper at this conference (Thornton *et al.* 1996a) presents revised natural durability ratings for the outer heartwood of mature timbers exposed in the ground. That simplified classification, which provides ratings for use within Australia, was developed using median specimen life values obtained as a result of exposing specimens in-ground for at least 25 years at five sites. The durability rating for a given species was the rating assigned at the site where the timber obtained its lowest median specimen life. Obviously this approach is very conservative and will dictate that, at some locations, even those with moderate hazards, timbers of variable or moderate durability not be used in ground contact.

In this paper, we propose an approach which we believe will be appropriate in the current FWPRDC project on a "reliability-based durability design method". The approach will allow the data from each test site to be used, as well as data from our accelerated field simulator (AFS). If we consider that each site offers some combination and level of decay and termite hazard, we can report how timbers performed under those conditions for more than 25 years. Performance will be to give a lower value for the "moderate decay, moderate termite" hazard than it was for the "moderate decay, no termite" hazard. This approach is justified by the observation that, in regions with termite hazards, not all specimens will be attacked by termites. Hence, a value equivalent to that for the "moderate decay, no termites" hazard should be applied.

3. High decay, low termites. Values for Pennant Hills were used. Calculation of MEDSL values was based on the most attacked cross-section, which was almost invariably due to decay.

4. High decay, high termites. The higher value of those from Pennant Hills and Innisfail. See item 2 for approach taken.

5. Very high decay, low termites. Values for Jolly's Lookout were used. Calculation of MEDSL values was based on the most attacked cross-section, which was almost invariably due to decay.

Very high decay, extremely high termites. We don't have data from a site with hazard combinations of very high decay and very high termites. However, we feel that this hazard, especially in terms of the very high termite hazard, relates to what may be expected at least at some sites with *Mastotermes darwiniensis* present. We believe that, until we have the appropriate data, the results for the "extremely high decay, extremely high termites" hazard should be used.

6. Extremely high decay, no termites. Values from the AFS decay tests (Thornton *et al.* 1995a, b) were used. These results accommodate the possibility of an in-ground decay hazard in northern Australia that exceeds the decay hazard at Jolly's Lookout. Until such areas are identified, and perhaps the rate of biodeterioration in ground verified, these values should be used cautiously (see later discussion).

7. Extremely high decay, extremely high termites. The higher value of the AFS decay and AFS decay plus termites tests (Thornton *et al.* 1995b) was used.

For both durability ratings and rates of deterioration, some adjustments have been made to fulfil the following requirements for a natural progression of change.
For each timber, values for decay in the absence of termites must either progressively increase or stay the same, as the hazard level for decay increases from moderate to high, high to very high, and very high to extremely high. Similarly, for each timber, values for decay with termites must either progressively increase or stay the same, as the hazard level of termites increases from moderate to high, and high to extremely high. In both of these cases any values representing a progressively reduced value were replaced by the higher value already given for the lower hazard level.

RESULTS AND DISCUSSION

The hazard-based natural durability ratings

Table 2 presents hazard-based natural durability ratings determined for timbers exposed to various combinations and levels of hazards. Because we express our data on the basis of median specimen life (for a timber species exposed to a certain hazard combination), the variability observed in timber performance is related to its hazard-to-hazard performance. Hence, when we apply the ratings to a single hazard combination this variability is eliminated. This approach allows timbers whose performance varies greatly to have their durability matched to a site's hazards. For example, *E. marginata* was found to be variable in its susceptibility to decay. At the three sites, it rated 1, 2 and 3. For the conservative approach taken for the generalised natural durability ratings, (Thornton *et al.* 1996a) *E. marginata* was rated a 3/2 for use anywhere. Under the hazard-based ratings, *E. marginata* would be considered a 1, 2 or 3, depending on the hazard of the site where it was to be used.

The problem with proposing a classification with many combinations and levels of decay and termite hazards is that the classification, to be useful, must delimit the areas within Australia where each combination might apply. We hope and expect that the durability design project will be able to resolve this problem by producing hazard maps. In the meantime, this proposal may be of limited applicability.

The resistance of the timber species to increasing hazard levels is particularly interesting. Obviously, the most durable species are the ones that retain their high durability rating when the hazard levels, whether in the field or AFS, are increased.

Rates of biodeterioration

Table 3 presents mean rates of biodeterioration, in millimetres per 10 years, from each face. Numbers are given to one decimal place in order to provide more accurate data for the most resistant timber species. There will undoubtedly be more interest in the most resistant timbers than the least resistant ones. Natural durability publications are usually sought by persons wanting to use or specify the more resistant of the available timbers. This is just as well because, for less durable timbers at "high decay, high termite" hazard levels (Table 2), sufficient dimensions of outer heartwood would not be available in order to remain serviceable for more than 10 years. At this stage, the best timbers are deteriorating at less than approximately 4 mm per ten years. Inspections will need to be carried out until median specimen lives are determined for more accurate figures to be obtained. After another 10 years' exposure, any timbers that have not yielded median specimen life values will have rates of <3.0 mm per 10 years.

The suggested approach for the designer/specifier for using the data in Table 3 is to ascertain the service life (in decades) required of the in-ground members used in structures, then to multiply the values given, under a suitable hazard level(s), to determine the expected loss from each face. Such expected loss would have to be considered as a "sacrificial" dimension to be allowed for on the "outside" of whatever cross-sectional dimension is required to be fit for strength purposes.

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Table 2: Hazard-based natural durability ratings of the outer heartwood of Australian timbers in ground contact

Combination of Decay and Termite Hazard levels in-ground in Australia

Species	Moderate Decay No Termites	Moderate Decay Moderate Termites	High Decay Low Termites	High Decay High Termites	Very High Decay Low Termites	Extremely High Decay No termites	Extremely High Decay Extremely High Termites
Australian hardwoods (Myrtaceae)							
E. acmenoides (White mahogany)	1	1	1	1	1	2	2
E. amygdalina (Black peppermint)	4	4	4	4	4	4	4
E. astringens (Brown mallet)	1	2	1	2	2	2	3
E. bosistoana (Coast grey box)	1	2	1	2	1	2	3
E. botryoides (Southern mahogany)	2	2	2	3	3	3	4
E. calophylla (Marri)	3	3	3	3	4	4	4
E. camaldulensis (River red gum)	1	2	2	2	2	2	2
E. capitellata (Brown stringybark)	3	4	3	4	3	4	4
E. caldocalyx (Sugar gum)	1	1	1	1	1	1	1
E. cloeziana (Gympie messmate)	1	1	1	1	1	2	2
E. consideniana (Yertchuk)	2	2	2	3	2	4	4
E. cornuta (Yate)	1	3	2	3	2	2	4
E. cypellocarpa (Mountain grey gum)	3	4	3	4	3	4	4
E. diversicolor (Karri)	2	4	2	4	3	3	4
E. dives (Broad-leaved peppermint)	3	3	3	3	3	4	4
E. elata (River peppermint)	4	4	4	4	4	4	4
E. eugenioides (White stringybark)	3	3	3	3	3	3	4
E. eugenioides (Wilkinson's stringybark)	4	4	4	4	4	4	4
E. fastigata (Brownbarrel)	4	4	4	4	4	4	4
E. globulus (Tasmanian blue gum)	3	4	3	4	3	3	4
E. globulus (Maiden's gum)	3	3	3	4	3	3	4
E. gomphocephala (Tuart)	1	2	1	3	1	2	3
E. goniocalyx (Long-leaved box)	2	2	3	3	3	3	4
E. grandis (Rose gum)	4	4	4	4	4	4	4
E. guilfoylei (Yellow tingle)	1	3	2	4	2	2	4
E. haemastoma (Scribbly gum)	2	2	2	3	3	4	4
E. jacksonii (Red tingle)	3	4	3	4	4	4	4
E. leucoxylon (Yellow gum)	1	1	3	3	3	3	3
E. longifolia (Woollybutt)	1	1	1	2	1	2	3
E. macrorhyncha (Red stringybark)	2	2	2	2	2	3	3
E. maculata (Spotted gum)	1	2	2	2	2	2	3
E. marginata (Jarrah)	1	2	2	2	3	3	3
E. megacarpa (Bullich)	2	4	2	4	3	4	4
E. melliodora (Yellow box)	1	1	1	1	1	1	1
E. microcorys (Tallowwood)	1	1	1	1	1	2	2
E. moluccana (Grey box)	1	1	1	2	1	1	2
E. muelleriana (Yellow stringybark)	2	3	3	4	3	3	4
E. obliqua (Messmate)	4	4	4	4	4	4	4

E. paniculata (Grey ironbark)	1	1	1	1	1	1	2
E. patens (WA blackbutt)	2	2	2	4	2	3	4
E. pilularis (Blackbutt)	2	2	2	3	3	3	4
E. polyanthemos (Red box)	1	1	1	1	1	2	2
E. radiata (NSW messmate)	4	4	4	4	4	4	4
E. regnans (Mountain ash)	4	4	4	4	4	4	4
E. resinifera (Red mahogany)	1	2	2	2	2	2	2
E. rubida (Candlebark)	4	4	4	4	4	4	4
E. saligna (Sydney blue gum)	2	3	2	3	3	3	3
E. salmonophloia(Salmon gum)	1	2	2	3	2	2	4
E. sideroxylon (Red ironbark)	1	1	1	1	1	1	1
E. sieberi (Silvertop ash)	2	3	2	4	3	3	4
E. tereticornis (Forest red gum)	1	1	1	1	2	2	2
E. viminalis (Manna gum)	4	4	4	4	4	4	4
E. wandoo (Wandoo)	1	1	1	1	1	1	1
L. confertus(Brush box)	4	4	4	4	4	4	4
L. suaveolens (Swamp box)	2	2	2	2	2	3	3
S. glomulifera (Turpentine)	1	1	2	2	2	3	3
S. hillii (Satinay)	1	1	2	2	3	3	3
Australian hardwoods other than Myrtaceae							
A. acuminata (Raspberry jam)	1	1	1	1	1	1	1
A. harpophylla (Brigalow)	1	2	1	2	1	1	2
A. luehmannii (Bull oak)	1	2	1	2	1	1	2
L. reticulata (Bollywood)	4	4	4	4	4	4	4
N. cunninghamii (Myrtle beech)	4	4	4	4	4	4	4
Exotic hardwoods							
A. thyrifera (Garawa)	4	4	4	4	4	4	4
I. bijuga (Kwila)	2	2	3	3	3	3	3
P. indicus (NG rosewood)	3	3	3	3	3	3	3
Q. alba (American white oak)	4	4	4	4	4	4	4
T. grandis (Burmese teak)	1	1	2	2	2	3	3
Australian softwoods							
A. robusta (Kauri pine)	4	4	4	4	4	4	4
A. selaginoides (King William pine)	3	3	3	3	3	3	3
C. columellaris (White cypress pine)	1	2	2	2	2	2	2
L. franklinii (Huon pine)	3	4	3	4	3	4	4
P. asplenifolius (Celery-top pine)	3	3	4	4	4	4	4
P. mara (Black pine)	4	4	4	4	4	4	4
Exotic softwoods							
P. radiata (Radiata pine)	4	4	4	4	4	4	4
P. menziesii (Douglas fir)	4	4	4	4	4	4	4
S. sempervirens (Redwood)	2	2	3	3	3	3	3
T. plicata (Western red cedar)	3	3	3	3	3	3	3

3. IPM strategies in subterranean termite control in Australia

First, **integrated pest management (IPM)** is a decision making process for determining **IF** you need pest suppression treatments, **when** you need them, **where** you need them, and **what** strategy and mix of tactics to use. In IPM programs, treatments are not made according to a predetermined calendar schedule, they are made only when and where monitoring has indicated that the pest will cause unacceptable economic, medical or aesthetic damage. Treatments are chosen and timed to be most effective and least disruptive to natural mortality factors. In urban settings, IPM has been used to manage insect pests in parks, gardens, in shade trees and in timber-in-service in and around buildings, both domestic and industrial (Olkowski 1980).

4. Components of a termite IPM program

A termite IPM program contains the following key components:-

4.1. **Identification** of termite species causing damage.

4.2. **A monitoring and record keeping** system for regular sampling or inspections of termites. Monitoring is an ongoing activity throughout any IPM program.

4.3. **Damage level** - A determination of the economic or aesthetic damage level caused by termites sufficient to warrant control actions.

4.4. **Action levels** - The amount of termite activity is indicative of the population size, and a determination of other variables, such as season, amount of susceptible timber in the building, and so on, from which it can be predicted what damage levels will be reached within a certain time if no treatments are undertaken.

5. Main strategies in subterranean termite control.

There are three main strategies in subterranean termite control, namely,-

(1) **installation of barriers.**

(2) **impregnation of termite susceptible timbers with a wood preservative.**

(3) **destruction of the termite nest.**

5.1. Installation of chemical and physical barriers

In 1995, Standards Australia released Australian Standard AS 3660.1 entitled "Protection of buildings from subterranean termites. Part 1: New buildings (Anon 1995b). This Standard sets out methods of implementation during construction, for minimizing the risk to new buildings from damage by subterranean termites. It includes procedures and details for providing both physical barriers and toxic barriers. The Standard provides a range of options. Barriers may be used singly or in combination to provide an integrated system for the protection of buildings.

The chemical soil barriers registered for use are the organophosphate, chlorpyrifos (Dursban), and the synthetic pyrethroid, bifenthrin (Biflex). Barrier treatments may be applied as full, under-slab treatments, and partial or perimeter treatments. Also, reticulation systems are permissible.

Physical barriers such as metal shields, Granitgard® and Termi-Mesh® that are fitted around pipes through slab contructions, are designed to impede and discourage termite entry into a building (French 1989). Though not in the present Standard (AS 3660.1-1995) Granitgard® has shown promise as a termite barrier when retrofitted around test buildings in a field trial at Walpeup, Victoria, that has been successfully prevented termite penetration for nearly 4 years (Ahmed and French 1995).

While termites can build around and over both chemical and physical barriers they are then in the open where they can be detected more readily during regular (competent) inspections. It must be emphasised that termites can bridge or breach barrier systems and that thorough regular inspections of the building are necessary (Anon 1995b).

5.2. Impregnating termite susceptible timbers with a wood preservative.

Australian Standard AS 1604 (1993c): Timber-Preservative-treated-sawn and round, specifies the preservative treatment level to protect timber from termite infestation in the four major hazard levels of timber performance where termites might occur. These are, interior above ground (H2); exterior above ground (H3) and exterior in ground contact (H4 and H5). Timbers may be protected against termites using remedial preservative treatments, and several novel copper boronaphthenate pastes and other diffusible copper-boron preservatives, suitable for both softwoods and hardwoods, have been developed at the Division in recent years.

The use of naturally termite-resistant timbers (see AS 3660.1, pp. 52-54) may also be an option. But such timbers may be difficult to obtain in any commercial quantity, and the different timber species listed have different levels of resistance to various species of termite.

5.3. Destruction of the termite nest.

There are two main approaches in termite nest destruction, namely, (i) if nest is located, and (ii) if nest not located.

5.3.1. If nest is located:

Nests may be eradicated by a skilled and trained operators with arsenic trioxide, chlorpyrifos, bifenthrin, or a suitable gas fumigant, or using bait toxicants. Whatever the selected method of eradication, the application of dust and/or bait toxicants involves aggregating large numbers of termites with an appropriate baiting system (French and Ahmed 1995).

When using a **dust toxicant**, the aggregated termites are removed from the bait containers, dusted with an appropriate dust toxicant, and released back into the container, and from there, back into the active termite colony network. On grooming each other, the toxicant is spread throughout the colony, leading to its eventual collapse (French 1991, 1994, French *et al.* 1995).

The insertion of **bait toxicants**, via application into or on suitable cellulosic substrates into the bait container is known as the "bait-block method of termite control" (Beard 1974). The bait toxicants act as delayed action stomach poisons with minimum contact action. Compounds such as Amdro (Su *et al.* 1982), fluorinated lipids (Prestwich *et al* 1983), insect growth regulators (Su *et al.* 1985, Su, 1994) and mirex (Beard 1974, Paton and Miller 1980, French 1988). La Fage (1984) considered the bait-toxicant method the "holy grail" of termite control. Currently, we are testing a fluorophenyl urea that is showing considerable promise as a bait toxicant.

5.3.2. If nest not located:

When the nest cannot be located, then a baiting technique is required. On locating termite activity outside/inside the building, a suitable bait container (box, pipe, plastic container, wood block, etc.) needs to be placed alongside, or onto active termite galleries or sheltertubes in order to aggregate large numbers of foraging termites. When sufficient numbers of termites have been aggregated, termite eradication can occur using an appropriate dust or bait toxicant. Details of these techniques may be found in French (1994).

6. Choice of termite control measures

Over the years many termiticides and termite control methods have been proposed worldwide, but in this paper the focus is on those applied in developed countries (French 1986, 1991, 1994, Mauldin 1986, Lenz *et al* 1988, Watson 1988, McDaniel and Kard 1995). Rather than describe in detail each and every alternative termite control strategy available for subterranean termite control in Australia, the strategies have been summarised in **Table 2.** The term **Pre-treatment** refers to complete or partial chemical soil-barrier and physical barrier treatments for buildings under construction, while the term **Post-treatment** refers to complete or partial treatments of existing buildings using a termite eradication method, either chemical or non-chemical (e.g., Electro-Gun technique to eradicate drywood termite nests). Both these terms refer in turn to Australian Standard AS 3660.1, 1995: Protection of buildings from subterranean termites Part 1: New buildings. Part 2. Prevention, detection and treatment of infestation, is yet to be prepared and ratified by Australian Standards.

Table 2 has been arranged to reflect the three main termite control strategies mentioned above. What strategy and mix of tactics to use by a pest control operator at any time will vary from situation to situation. What should not vary is the rigour and order with which the operator applies the IPM procedure. Detailed procedures of any individual strategy may be obtained by consulting the appropriate references listed in this paper, or by contacting the authors in CSIRO.

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Table 1-- The major termiticides used in subterranean termite control worldwide.

Region	Country	Termiticides used[1]					
		OC	OP	SP	GAS	AS	Other
Ethiopian	Ghana	+	+	+	+	+	
	Nigeria	+				WP	
	South Africa	+	+	+	+	+	WP
	Tanzania	+	+				
	Uganda		+			+	
Palearctic	China (Nanjing)		+		+	+	Mirex
	France		+	+		+	IGR
	Greece	+	+	+			
	Israel	+	+	+			
	Italy	+	+	+			
	South Korea	+	+			+	
	Spain	+	+	+		+	
	Yugoslavia	+					
Oriental	India	+			+	+	WP
	Indonesia	+		+		+	
	Japan		+	+	+		WP
	Philippines	+					
Australian	Australia		+	+	+	+	Mirex. NCB. IGR
Hawaii and Oceanic Is.	Fiji	+			+	+	
	USA		+	+	+		NCB
Nearctic	Canada		+	+			IGR
	USA		+	+	+		IGR.EG
Neotropical	Bolivia	+				+	
	Columbia	+			+	+	
	Uruguay	+				+	

[1]OC = Organochlorine; OP = Organophosphate; SP = Synthetic pyrethroid; GAS = Fumigation; AS = Arsenicals; WP = Wood preservative treatment IGR = Insect Growth Regulator (e.g., hexaflumuron); NCB =Non-chemical termite barrier;. EG = Electro-Gun.

Table 2. IPM strategies in Australia for subterranean termite control

Strategy	Chemical /physical/ non chemical	Application	Pre-treatment Full	Pre-treatment Partial	Post-treatment Full	Post-treatment Partial
Barriers	Bifenthrin	Sprayed	+	+	+	+
	Chlorpyrifos	Sprayed	+	+	+	+
	Chlorpyrifos	Reticulated	+	+	+	+
	Granitgard	Installed	+	+	-	+
	Termi-Mesh	Installed	+	+	-	+
Wood Preservatives	CCA	Timbers	+	+	+	+
	Borates	Timbers	+	+	+	+
	LOSP	Timbers	+	+	+	+
	PEC	Timbers	+	+	+	+
	PROCCA	Timbers	+	+	+	+
Nest destruction	As_2O_3	Bait/dust	-	-	-	+
	Borates	Bait/dust	-	-	+	+
	IC*	Bait/dust	-	-	-	+
	Silafluofen*	Bait/dust	-	-	-	+
	IGR's*	Bait	-	-	-	+
	Mirex	Bait	-	-	-	+
	Coopex*	Dust	-	-	-	+
	Fumigant	Gas	-	-	-	+
	OP	Spray	-	-	-	+
	Electro Gun^{+}	Electrocution				+

CCA = Copper chromium and arsenic; LOSP = Light organic oil preservative; PEC = Pigmented emulsified creosote; PROCCA = Oil based copper chromium arsenic; As_2O_3 = Arsenic trioxide; IC = Inclusion compounds (CSIRO technology); * = Substances currently in test but not in Australian Standard AS 3660-1. 1996; IGR = Insect growth regulators (e.g., flurox; hexaflumuron; hydramethylnon; imidaclorprid); OP = organophosphate (chlorpyrifos);. + = Prospective termite control measure.

An accelerated field simulator study of the natural durability of heartwood from mature and regrowth trees

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ABSTRACT

Comparative decay resistance of the outer heartwood of slow and faster growing trees of ten timbers was determined after exposure for almost seven years in an accelerated field simulator. Statistical analysis of median specimen life values showed that specimens from mature trees of *Corymbia* (formerly *Eucalyptus*) *maculata*, *E. muelleriana* and *E. resinifera* were significantly more resistant than those cut from regrowth trees. However, no significant difference was found between mature and regrowth specimens cut from *Allocasuarina fraserana*, *C. calophylla*, *E. diversicolor*, *E. marginata*, *E. microcorys*, E. *patens* or *E. wandoo*.

INTRODUCTION

It is commonly believed that older trees that are growing slowly deposit more extractive compounds in their outer heartwood than do younger, faster growing trees (Nault, 1988). The types and amounts of these extractive compounds deposited in the heartwood by the living tree impart durability to the timber. The primary aim of this study was to determine whether the in-ground durability, with respect to decay, of specimens cut from the outer heartwood of regrowth trees was greater, less or the same as the durability of samples collected from the same zone of mature trees. Seven species of *Eucalyptus*, two of *Corymbia* (formerly *Eucalyptus*) and one of *Allocasuarina* were examined.

This study resulted from the mutual interest of CSIRO and the W.A. Department of Conservation and Land Management in the natural durability of timber and its implication for the utilization of Western Australia's existing and future timber resources. The initiation of this study, and results after 184 weeks of in-ground exposure were reported by Johnson *et al.* (1993).

MATERIALS AND METHODS

1. Species and sources of timber

The species of the regrowth and mature timbers are presented in Table 1, together with the number of replicates from each state. Samples from the older trees, (referred to as mature) were obtained from native forests in Western Australia, New South Wales, Queensland and Victoria. It was specified that the selected mature trees have growth rates and diameters typical of those being cut in commercial operations. Where estimates were given, the mature trees ranged in age from 100 to 500 years (Table 2). On the other hand, the samples from the younger, faster growing trees (referred to as regrowth) were obtained from native forests or plantations in Western Australia. Ages of regrowth trees ranged from 15 to 70 years (Table 2). A number of yardsticks were included to enable the durability of the test specimens to be gauged. They include heartwood of mature *Eucalyptus camaldulensis* Dehnh., regrowth *E. regnans* F. Muell. and *Pinus radiata* D. Don. It should be noted that, in a recent revision of the bloodwoods (Hill and Johnson, 1995), both *E. calophylla* and *E. maculata* were placed in the genus *Corymbia.*

2. Preparation of specimens

Billets were collected from the butt log of five trees chosen to be representative of the commercial timber present at the time of cutting in mature or regrowth forests of selected regions or, in some cases, from Western Australian plantations. The heartwood test specimens were cut from a zone 25 mm closer to the pith than the apparent sapwood-heartwood boundary. The 25 mm wide zone was avoided so that no specimens would be cut from any transition wood present. Transition wood is of lower natural durability than outer heartwood and would necessarily receive an unrealistically low rating. The sapwood-heartwood boundary of the hardwoods was located by the use of dimethyl yellow stain.

The green specimens were cut to a size of 25 x 25 x 120mm along the grain. After air-drying to equilibrium moisture content (12%), they were machined to 20 x 20 x 100 mm.

Table 1. Species and geographic sources of timbers used in this study[1]

Species	Common Name	Source & number of replicates Regrowth	Mature
Allocasuarina fraserana (Miq.) L. Johnson	WA sheoak	W5	W5
Corymbia calophylla (Lindl.) K. D. Hill & L.A.S. Johnson	Marri	W5	W5
C. maculata (Hook.) K.D. Hill & L.A.S.Johnson	Spotted gum	W4	Q5
Eucalyptus diversicolor F. Muell.	Karri	W5	W5
E. marginata Donn ex Sm.	Jarrah	W5	W5
E. microcorys F. Muell.	Tallowwood	W5	N1, Q4
E. muelleriana Howitt	Yellow stringybark	W5	N3, V2
E. patens Benth.	WA blackbutt	W5	W5
E. resinifera Sm.	Red mahogany	W5	Q5
E. wandoo Blakely	Wandoo	W5	W5

[1] Geographic sources: N refers to New South Wales, Q to Queensland, V to Victoria and W to Western Australia.

3. **Exposure in the Accelerated Field Simulator (AFS)**

Test specimens were installed with three-quarters of their length in a sandy loam soil (Newell, 1961) collected from Walpeup, Victoria. Litter from the same site was distributed over the soil surface. The specimens were installed in seven rows of 25 specimens in a completely randomised design. Five trees of each species contributed an outer heartwood specimen to this study. Five *E. regnans* and *P. radiata* trees contributed the low durability, heartwood, yardstick timbers. *E. camaldulensis* was the higher durability yardstick. Additional species and treatments not discussed here were included (see Johnson *et al.*, 1993).

The AFS was maintained in darkness at 27-28° and at approximately 85% relative humidity.

4. **Inspection method**

Each specimen was removed from the soil and probed with a scalpel to determine the location and amount of decay present. Each specimen was rated, for cross-section lost to decay, on a scale ranging from 8 (sound) down to 0, in unit steps. A score of 3 or less, representing a cross-section loss of two-thirds or more, was considered to indicate that the specimen was unserviceable. Inspections were carried out at eight-week intervals for 353 weeks.

5. **Statistical analyses**

The data were treated as survival data; survival time being the time until a specimen scored 3 or less. A survival function over time *t* was defined as the probability that an item was serviceable at least to time *t*. For each wood species, a separate survival curve for regrowth and mature timber was estimated. These curves are based on an estimate of the survival distribution (Kaplan-Meier survival curve). The survival curves were compared using the Mantel-Haenszel log rank test (Collett, 1994). The analyses were carried out using the S-PLUS for Windows package from Statistical Sciences Inc.

Table 2 - Relevant characteristics of the regrowth and mature timbers[1]

	Regrowth				Mature		
Species	Est. Age (yrs)	Mean Est.Age (yrs)	DBHOB (mm)	Air-dry density (kg/m³) x (SD)	Est. Age (yrs)	DBHOB (mm)	Air-dry density (kg/m³) x (SD)
Allocasuarina fraserana	25-50	36	250-350	717 (46)	100-125	240-500	737 (36)
Corymbia calophylla	35-60	43	260-400	863 (109)	150-300	470-607	850 (120)
C. maculata	21-45	28	180-320	829 (91)	*	*	1080 (22)
Eucalyptus camaldulensis	—	—	—	—	340->450	—	924 (75)
E. diversicolor	15-20		300-400	883 (17)	100-500	700-1200	880 (47)
E. marginata	30-50	40	270-350	816 (104)	200-300	650-1000	857 (111)
E. microcorys	21-52	28	180-325	906 (89)	*	*	982 (45)
E. muelleriana	19-28	23	200-300	684 (38)	*	180-470	851 (119)
E. patens	40-60	48	240-400	903 (141)	150-300	460-750	915 (59)
E. regnans	50	50	*	594 (38)	—	—	—
E. resinifera	21-52	28	180-300	733 (93)	*	*	1021 (64)
E. wandoo	50-70	58	179-305	1068 (42)	150-300	320-575	1096 (21)
Pinus radiata	14-36	26	305-376	576 (143)	—	—	—

1 A dash indicates that this material was not investigated. An asterisk indicates that the data are not available, but in the case of estimated ages they were greater than 100 years.

Results and Discussion

It might be considered that any difference in heartwood durability of regrowth and mature trees of the same species was due to rate of growth or age of tree. It is widely believed that heartwood from slow-grown trees is more durable than that from fast-grown trees (Da Costa *et al.* 1961, Da Costa 1975, Wilkes 1984). However, the limited evidence from studies of eucalypts does not support this belief. Rudman (1964) reported no significant difference in decay resistance between *E. marginata* trees of the same age (>45 years) but different growth rates. Others (Bamber *et al.*, 1969) could not relate polyphenol content of plantation trees (*E. grandis*) to rate of growth. Wilkes (1984, 1985) found that faster-grown coppiced eucalypts (*E. albens* Benth., *E. bancroftii* (Maiden) Maiden, *E. dealbata* A.Cunn. Schau., *E. goniocalyx* F. Muell. Miq. and *E. macrorhyncha* F. Muell: Benth.) produced more extractives than did the slower-grown species of the same age (40 years). Despite this relationship, the effect of growth rate on heartwood resistance to deterioration was negligible.

It is documented that age of tree has an effect on eucalypt durability. Juvenile wood, which is produced by eucalypts for eight to 12 years (Nelson and Heather 1972, Hillis pers. comm.), has a low basic density, short fibre length, thin cell walls and low content of extractives. Because the extractives confer durability (Rudman, 1964) but are low in juvenile wood, heartwood from trees still producing juvenile wood is of lower durability. Furthermore, fully mature heartwood may not be produced until the tree is up to 35 years of age (Bamber and Curtin 1974, Wilkes 1984).

The median and average specimen lives of the ten timber species in our study are presented in Table 3. Results of statistical analysis comparing the shape of the survival curves of the regrowth and mature specimens are given as *p* values. No significant difference was found between the mature and regrowth specimens cut from the following seven species: *A. fraserana, C. calophylla, E. diversicolor, E. marginata, E. microcorys, E. patens* and *E. wandoo*. These findings support the limited published data indicating that there is no difference in durability of outer heartwood from faster-grown regrowth trees versus that from slower-grown mature trees.

However, the specimens from mature trees of *C. maculata, E. muelleriana* and *E. resinifera* were found to be significantly more resistant to decay than those cut from regrowth trees. The seven species that showed no significant difference in decay of regrowth and mature specimens also had little difference in mean air-dry density (see Table 2). Density differences ranged from 3 to 76 kg/m^3. By contrast, the three species with significantly less decay of mature than regrowth specimens also had the greatest differences in air-dry density. The mature specimens had densities 167, 259 and 288 kg/m^3 greater than the corresponding regrowth material.

Chafe (1989) showed a close relationship between tentative durability of outer heartwood and basic density of 38 species of mature eucalypts. In our study we have identified a significant relationship ($p<0.001$) in Cox's proportional hazards model between air-dry density of outer heartwood and service life of many of the same timber species examined by Chafe. The statistical processing of the data supports the finding that, if the air-dry density of regrowth heartwood is similar to that of mature heartwood, the durability will also be similar. These two studies point the way to what may eventually prove to be a simple way of determining the relative durability of regrowth heartwood. While such a relationship appears to be true for the myrtaceous hardwoods studied here, much more work needs to be carried out to see if this relationship is valid, for example, for other Myrtaceae as well as for other timbers.

Table 3. Median specimen life (MEDSL) and average specimen life (ASL) values determined from specimens exposed 353 weeks in the AFS[1].

Species	MEDSL (weeks)		ASL (weeks)	
	mature	regrowth	mature	regrowth
A. fraserana	213	189	204	195
C. calophylla	225	237	210	225
C. maculata,	—	277**	—	277
E. diversicolor	197	205	194	210
E. marginata	164	225	188	225
E. microcorys	—	261	—	—
E. muelleriana	261	124*	234	127
E. patens	237	237	223	238
E. resinifera	—	148**	—	161
E. wandoo	—	—	—	—
yardstick timbers:				
E. camaldulensis, mature	261		242	
E. regnans, regrowth		44		50
P. radiata, regrowth		68		70

1 Test specimens were heartwood and each species, except the yardsticks, was represented by five mature and five regrowth specimens.
— Indicates that insufficient replicates have become unserviceable to allow calculation of the MEDSL or ASL.
* Statistically significant at the 5% level.
** Statistically significant at the 1% level.

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THE EFFECT OF PRESSURE TREATMENT WITH LIGHT ORGANIC SOLVENT PRESERVATIVE ON STRENGTH PROPERTIES AND DRYING BEHAVIOUR OF SLASH PINE.

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ABSTRACT

Results are presented of a study conducted on behalf of Koppers Hickson, which investigated post treatment drying behaviour and the mechanical properties of slash pine (*Pinus elliottii* Engelm. var. *elliottii* L. & D.), that had been pressure treated with Light Organic Solvent Preservative (LOSP).

Results indicate that kiln drying after treatment at 40°C resulted in the accelerated removal of residual solvent when compared to air drying, although some moisture was also removed, which resulted in distortion to some of the boards. For the 70 pieces of 70mm x 35mm framing used in the study, there was no negative effect of LOSP treatment on mechanical properties, after either air drying or kiln drying.

INTRODUCTION

This paper presents the results of a study conducted on behalf of Koppers Hickson, which investigated post treatment drying behaviour and mechanical properties of slash pine (*Pinus elliottii* Engelm. var. *elliottii* L. & D.), that had been pressure treated with Light Organic Solvent Preservative (LOSP). Specifically, the objectives of the study were to:

- compare the rates of removal of residual solvent by air drying and kiln drying, of stickered and block-packed stacks, and
- to expose any effect of LOSP treatment followed by either air or kiln drying on the mechanical properties of a sample of 2.4m x 70 mm x 35 mm studs.

MATERIALS

A sample of 70 pieces of 70mm x 35mm slash pine each 5.4m long was purchased from a commercial softwood framing supplier. This sample was chosen to represent normal output from a softwood sawmill producing framing timbers. i.e. high temperature kiln dried, to between 10% and 15% moisture content, dressed and graded.

METHOD

Sample Preparation

Each 5.4 m piece of framing was docked to provide two matched samples of 70 pieces each of 2.4m lengths. An additional matched group of pieces 300mm lengths was also recovered and later used as untreated control samples for small clears strength tests. The cutting pattern is shown in Figure 1

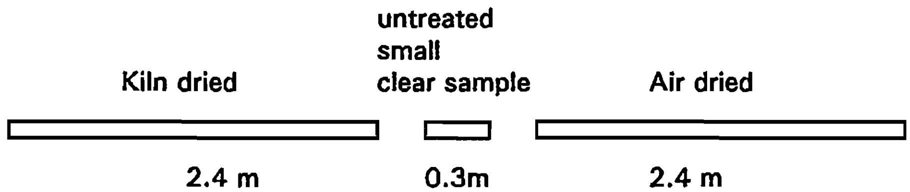

Figure 1: Sample preparation cutting pattern

Treatment

Each matched set of 70 x 2.4m lengths was treated to meet H3 requirements, with an LOSP timber preservative to an uptake of approximately 50 litres per cubic metre. Treatment was undertaken at the DPI, Salisbury Research Centre using an experimental scale, pressure treatment cylinder.

Drying

To examine the drying behaviour of LOSP treated slash pine, each set of 70 matched pieces of 70mm x 35mm x 2.4m was either kiln dried at 40°C or air dried. Each matched group of 70 pieces was also divided in to two sub groups of 35 pieces and each of these sub groups was either block stacked or stickered during drying. Board weights were recorded before treatment, immediately after treatment, and at intervals of 24, 48, 72, 96, and 168 hours after treatment. Proportional mass loss was calculated to indicate residual solvent content. This method was designed to compare the effectiveness of each drying regime.

Strength Properties

For each of the 140 x 2.4m pieces, MOE was determined using a machine stress grader (MSG), before and after treatment. In addition to these data, MOE and MOR were determined for small clear samples (20mm x 20mm x 300mm) taken from untreated samples, treated and air dried samples, and treated and kiln dried samples.

RESULTS

Treatment

Matched samples from 25 randomly selected pieces were cut at a minimum of 500mm from one end of each section. The assessment of the treatment indicated that the samples passed the penetration requirements of the 1987 Timber Utilisation and Marketing Act (TUMA) 1987.

Drying

Figure 2 shows drying rates for each of the drying regimes used in the study. The figure shows clearly the increased rate of post treatment mass loss that is achieved by kiln drying and stickered stacks compared to air drying, and block-packed stacks.

Note that the negative residual mass values for kiln dried samples represent water loss in addition to solvent loss. The stacks dried in the kiln were unrestrained and as a consequence, substantial distortion occurred in some pieces. Air dried samples did not distort in the same manner as kiln dried samples. In order to avoid distortion due to post treatment kiln drying, use of stripped stacks restrained with weights and kiln conditions maintained at an equilibrium moisture content equivalent to that of the desired in-service moisture content. e.g. 11% is recommended.

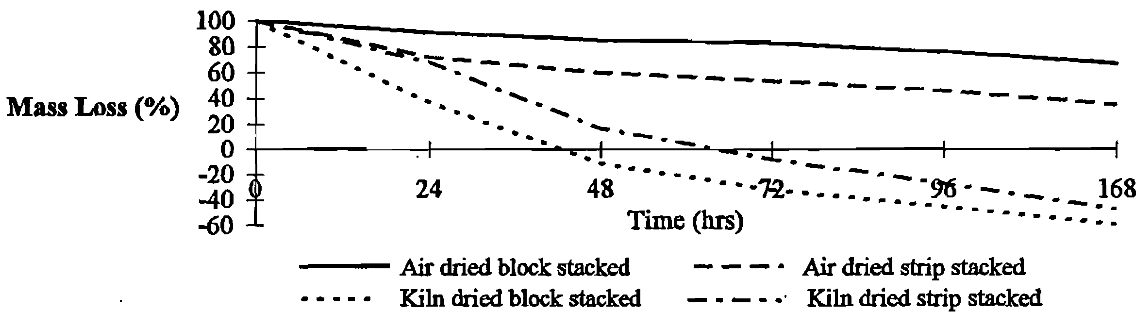

Figure 2: Drying Record for LOSP Treated Slash Pine

Strength Properties

Figures 3 and 4 show pre treatment versus post-treatment MOE values for machine stress grading, of air dried and kiln dried samples. A regression line relating pre and post treatment values has also been shown in addition to a line indicating a direct relationship. The proximity of the regression fit to the direct relation fit indicates the magnitude of the effect of treatment and drying.

Statistical tests established that there was no significant difference (p=0.1) between means for pre treatment values compared to post treatment values, for the air dried samples. For the kiln dried samples, a significant difference (p=0.01) was established for pre and post treatment mean values. The stiffness for kiln dried samples was increased after treatment and drying. This is to be expected due to the reduction of moisture content that occurred during post treatment kiln drying.

Table 2: Statistical Comparison of Basic Permissible Stress for Untreated and Treated Kiln Dried and Air Dried Samples

TREATMENT/ DRYING	UNTREATED	KILN DRIED (AND TREATED)	AIR DRIED (AND TREATED)
No. Samples	70	70	70
R_{mean}	87	90	86
$R_{st.dev}$	20	20	17
R_{CofV}	0.23	0.22	0.20
$R_{0.05}$	56	56	60
R_k	52	52	56
R_{basic}	20	20	22

The results indicated no significant difference (p=0.1) between pre treatment values of basic strength (R_{basic}), and post treatment values, for both kiln dried and air dried samples. The results do however show significant difference (p=0.1) between pre treatment and post treatment values of characteristic stiffness (E_k) for both kiln dried and air dried samples. In both cases, the characteristic stiffness is greater in the post treatment results than for the pre treatment.

CONCLUSION

The results of the study indicate that air drying of stripped packs has been the most effective method for removing residual solvent after treatment. However where processing time is critical to marketing, and kiln drying is adopted, kiln conditions should be controlled to maintain constant moisture content, and stacks should be restrained using weights. This will minimise the levels of distortion that can occur if this method is used.

The study has shown that pressure treatment of slash pine using light organic solvent preservative, and redrying either in the air or in a kiln at 40°C, has had no negative effect on the stiffness and strength of the wood.

This study has been effective in indicating the effect of LOSP treatment and post treatment drying on the mechanical properties of slash pine. In order to formally establish the structural properties of LOSP treated slash pine, a more detailed in-grade study should be undertaken according to the in-grade evaluation method described in AS/NZS 4063.

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Continued development of Granitgard® particulate termite barriers.

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Abstract

Granitgard[1] is superficially simple technology; graded crushed aggregate, sieved to a size range impenetrable to termites. However, behind this apparent simplicity lies a large research effort. In this paper we describe experiments to define the performance and characteristics of Granitgard and Granitgard stone candidates.

Introduction

Granitgard is a physical termite barrier system originating from Forestry and Forest Products research (French 1989), developed under licence by E.B. Mawson & Sons Pty Ltd of Cohuna in northern Victoria, through its subsidiary Granitgard Pty Ltd. Under a cooperative research agreement with CSIRO, Granitgard Pty Ltd maintains staff at the Forest Products Laboratory. Granitgard was first installed in Victoria seven years ago and has now been installed in all states except Tasmania as a barrier to subterranean termites.

Subterranean termites typically gain entry to structures from the soil below, by either excavating voids in the substrate or by simply walking through existing cavities. Granitgard principally excludes termites because (i) most of the particles are too large to be transported by the termites, and (ii) the voids between the particles are too small to allow termites to pass.

The original specifications for Granitgard were based on material produced from a single quarry and plant. A major focus of the collaborative research effort has been the evaluation of candidate stone from other sources around Australia as further suppliers of Granitgard. However, for the purposes of this paper, we report only on the development of materials for use in the tropics. Selection of an appropriate source (apart from economic and production factors) depends on three main factors:

1. **Hardness.** The stone must be sound (*see* Moye 1955, Dearman 1995) and sufficiently hard to remain undamaged from the actions of the termites. While most stone is considerably harder than the chitin of the insects' jaws, termite salivary and faecal excretions can be corrosive. As given in AS 3660.1(1995), sound igneous or metamorphic stone with a specific gravity of 2.52 or greater is generally suitable in this regard. In addition, the stone must exhibit a maximum wet/dry strength variation of not more than 35% (AS 1141.22, 1980) as measured using appropriately larger gradings from the same source.

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1 Granitgard is a registered trademark of Granitgard Pty Ltd, ACN 007 427 590.

2. **Size** of the particles is an important physical property, and the easiest to control. For standard (non-tropical) grade Granitgard, the AS 3660.1 "deemed to comply" specification, based on the performance of granite produced at Mawson's Pyramid Hill quarry, is as follows:

   "*. . . varying in size from 2.4-1.7 mm diameter . . . 100% passing a 2.36 mm sieve and less than 10% passing through a 1.18 mm sieve.*"

   It is possible to make an effective standard grade Granitgard barrier with some particles having diameters around 3.15 mm. There is a tolerance level for a few particles as large as 5 mm.

3. **Shape & crushing factors.** Particle shape is a critical factor in stone selection: a grading may be correct according to sieve analysis and yet allow termites free access if the particle shape is wrong. The mathematically ideal particle shape is a regular tetrahedron but unfortunately no natural stone crushes to this shape. At the extremes, the least tolerance is for shapes which either tend to the spherical, or are elongate flakes or slivers. Particles need to have sharp edges. This sharpness is easily lost in some types of crushing plant or if sieving is excessive or if the stone is insufficiently hard (see for example Briggs and Bearman 1996). Flakes are a problem when the termites can grip them with their mandibles and pull or jostle them free. Elongate particles can provide termite passage as they typically produce large voids due to reduced interdigitation of the particles beneath, evidenced by a smaller number of fringing particles. The aggregate must be reasonably clean. Fines or dusts adhering to the particles tend to act as a lubricant, greatly reducing the force termites need to dislodge larger particles.

Tropical Grades

Standard grade Granitgard is used in areas of Australia south of the Tropic of Capricorn where all the economically significant species of subterranean termites are similarly sized. North of this line, the Giant Northern Termite *Mastotermes darwiniensis* Froggatt (henceforth referred to as *Mastotermes*) is a significant pest in areas such as Broome, Darwin, Mt Isa and Townsville. It is absent from large areas of the wet tropics and has been collected south of the Tropic in central Queensland (Ratcliffe et al. 1952, Watson and Abbey 1993).

Table 1: Size of the Major Termite Pest Species (data from Hill 1942)

Termite Species	Body length *(mm)*		Head length *(mm)*		Head width *(mm)*	
	Max	Min	Max	Min	Max	Min
Coptotermes acinaciformis	5.10	3.80	1.75	1.25	1.15	0.80
Mastotermes darwiniensis	11.5	10.0	3.20	2.20	2.75	2.3

To exclude *Mastotermes* it is necessary to employ larger particles, but simply scaling up from standard grade Granitgard produces a grading which is readily penetrable by the smaller termites. The significantly larger size of *Mastotermes* (Table 1) means that many of the smaller particles in the standard grading of Granitgard present no real obstacle. To overcome this, production of a *Mastotermes* (tropical) barrier from a suitable stone source, requires a different range of particle sizes to accommodate the larger range of termite size and capabilities.

Materials and Methods

Assessment of potential graded stone barrier material is carried out using a standard laboratory jar-test procedure (Ewart 1996), which has evolved from the original development of Granitgard (French 1989), but is longer, uses greater numbers of termites, and provides for a standardised stone placement technique. Candidate stone is tested at a depth of 25 mm for standard grades and 50 mm for tropical grades.

It is a matter of physics that the weakest part of a particulate barrier will be its interface with a smooth surface as, at this point, the gaps between particles are greatly increased due to the reduced opportunity for interdigitation. In the jar-test, the particle barrier is presented to the termites in a transparent, semi-rectangular, smooth-walled container with tightly radiused corners, the theory being that the tight radius will expose any weakness in the barrier. Transparency allows monitoring of the termites' activity, vigour and health. The tests consist of five replicates and at least one control of readily-penetrable coarse or fine stone. In this test apparatus, the termites are initially restricted to a small matrix-filled volume in the bottom of the jar, which barely provides adequate space for the termites to move freely.

For testing with *Coptotermes acinaciformis* (Froggatt) (henceforth referred to as *Coptotermes*), termites are supplied with a matrix of suitably moistened *Coptotermes* mound material which may be diluted with inert filler to not less than 50% by volume. For testing with *Mastotermes*, termites are supplied with a different matrix. The standard CSIRO technique uses a moistened (3:1 water: matrix) mixture of vermiculite (nominal 5 to 10 mm particle size range) and *Eucalyptus regnans* F. von Mueller sawdust at 1:1 *w/w*. This matrix is much less dense than *Mastotermes'* normal habitat.

Imbedded in the matrix layer, a small food block of either *Pinus radiata* D.Don or *E. regnans* provides adequate nutrition. Candidate stone is then placed in the jar. The timber and matrix are sufficient to supply adequate nutrition for the life of the experiment. Thus the termite "pressure" on the candidate stone is much higher than it would be under natural conditions and exploring termites repeatedly examine and test the entire lower surface of the stone barrier. The jar test presents a worst-case scenario to test the candidate stone barrier's termite resistance.

Though Granitgard barriers are compacted in most building applications, specifications require Granitgard to be effective when loosely placed. Vibration or compaction of the sample greatly reduces the size of the interstitial spaces (Yu and Hall 1994) and lessens the risk of failure.

On top of the candidate stone, a single wooden block of either *P. radiata* or *E. regnans* is placed so as to provide a recruitment incentive to the termites. Pure water is added to the jar as required during the test to ensure adequate moisture.

Termites (*Mastotermes* and *Coptotermes*) are freshly collected by baiting either from mounds, infested trees or, directly from the ground. Baiting techniques developed for this program will be reported elsewhere.

Mastotermes and *Coptotermes* are tested separately against a common material.

would persist in their attack with such vigour and for such an extended period (if they did so, chemical soil barriers would, for example, regularly be breached by persistent sacrifice).

Table 2: Tropical Grade Granitgard Experiments						
Experiment Number	Material Tested Approximate sieve size passed[1]. Fine - generally under 2 mm Medium Coarse Very coarse - around 5 mm	Termite Species[2]	Duration (days)	Days to penetration of control	Days to maximum penetration	Result Pass / Fail[3]
1	VIC-1 Standard Grade Granitgard	*M*	23	1	1	F
2	QLD-1 Fine	*M*	22	1	1	F
3	QLD-2 Fine	*M*	15	1	1	F
4	QLD-1 Coarse + Very coarse	*M*	85	2	4	P
5	QLD-2 Very coarse + Medium + Fine	*M*	14	4	4	F
6	QLD-2 Very coarse + Medium	*M*	78	-	3	P
7	QLD-2 Very coarse + Coarse + Medium	*M*	69	1	2[4]	F
8	QLD-2 Graded as Standard Granitgard	*M*	69	1	36	F
9	QLD-2 Coarse + Medium	*C*	45	4	10	P
10	QLD-2 Very coarse	*C*	45	4	24	P
11	QLD-2 Coarse + Very coarse	*M*	46	10	24	F
12	QLD-2 Bimodal mix #1	*C*	41	3	6	P
13	QLD-2 Bimodal mix #1	*M*	41	7	33	F
14	QLD-2 Bimodal mix #2	*C*	47	2	35	P
15	QLD-2 Bimodal mix #2	*M*	47	9	12	P
16	QLD-2 Very coarse + Coarse	*M*	47	5	12	P
17	QLD-2 Very coarse	*M*	47	5	2	P
18	QLD-2 Very coarse	*C*	7	2	5	F
19	QLD-2 Coarse	*C*	21	3	3	F

1. Exact dimensions and gradings are commercially sensitive information.
2. *C* = *Coptotermes acinaciformis*, *M* = *Mastotermes darwiniensis*
3. P = Pass, F = Fail
4. All replicates penetrated by day two

The failure of the first bimodal grading (13), is difficult to explain in terms of the particle barrier alone, since the other experiments clearly show that the termites usually move much more quickly to defeat a barrier than 30 days, and even then the failure of three replicates almost simultaneously is most unexpected. The explanation seems to lie in a difference of feeding behaviour between *Coptotermes* and *Mastotermes*. *Coptotermes* heavily cement their excavations, supporting the stone particles with their galleries. *Mastotermes* working the vermiculite-sawdust matrix do not line their tunnels and, where particles are removed, this leads to cave-ins. The observed failures in 13 are most probably due to such cave-ins where the candidate material from above, falls into the void created by the termites' consumption of their food block. The phenomenon is possibly exacerbated by (i) vibration of the jars (observer effects) during measurement and maintenance and (ii), the low bulk density of the holding matrix. The cave-ins did not occur until the *Mastotermes* had mostly consumed their wood block. This situation does not arise in actual use, as Granitgard is not installed above any timber.

The other tests show the efficacy of larger stone against *Mastotermes* (4, 16, 17) and also *Coptotermes* (9, 10). It is a function of the near ideal particle shape of the candidate quarries' material (QLD-2) that we have been able to demonstrate a particulate barrier to *Coptotermes* composed of stone particles significantly larger than used in standard grade Granitgard sourced from elsewhere.

Conclusion

It is possible to exclude *Mastotermes* with a specially graded particulate barrier of crushed aggregate, in the same manner as standard grade Granitgard is installed below the Tropic of Capricorn. Further, we can now install a barrier using a bimodal particle distribution, which will exclude both large and small economically significant termite species.

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Testing and Development of Preservative Treatments for House Framing

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ABSTRACT

Field studies on the efficacy of preservative treatments for protecting interior structural lumber from attack by termites using a simulated house structure methodology have been established in Townsville, Qld against *Coptotermes acinaciformis* and in Hilo, HI against *Coptotermes formosanus*.

Data from a completed 12 month field test carried out in Hilo, HI are reported for treatments with chromated copper arsenate (CCA Type C), disodium octaborate tetrahydrate (DOT), amine copper quat (ACQ Type D), deltamethrin and untreated controls. Destruction of untreated structures was almost complete after the 12 months exposure with structural failure being apparent. CCA provided excellent protection giving a protection threshold of approximately 2.1 kg/m^3 while the ACQ Type D treatment was somewhat more prone to breakthrough of the treated zone into untreated heartwood regions and showed an equivalent threshold of approximately 4.0 kg/m^3. Borate treatment was subject to attack at all retentions tested providing an equivalent protection threshold retention in excess of 24.0 kg/m^3 DOT. Deltamethrin treatment provided complete protection to the test structures at the retentions tested, with no attack at retentions of 0.001 kg/m^3 after 12 months in test.

The on-going tests include the use of CCA, ACQ, borates and deltamethrin as a treatment of radiata pine in tests in Townsville, Queensland, and of Douglas fir in a new series of tests in Hilo, HI.

INTRODUCTION

Recent changes in the type and use of soil treatments for the prevention of ingress of termites into structures has led to opportunities in the area of H1 and H2 treatments for structural lumber not exposed to weather in service. Treatment of such materials is common in countries such as Japan (for *Coptotermes formosanus*), New Zealand (for *Anobium punctatum*), the Caribbean region (for a variety of termite hazards), Germany (for *Hylotropes bajulus*) and in certain regions of the U.S. such as Hawaii (Wilcox, 1984) (for *Coptotermes formosanus*). In Australia, the use of treatments for structural lumber in interior construction is not widespread, but this market has potential to develop significantly beyond its current base as changes in materials and regulations affect the use of soil treatments as the primary protection method against termite attack in houses.

In regions where termite protection has been the primary goal, chromated copper arsenate (CCA) has been the preservative of choice. In contrast, for regions where protection only from wood-boring beetles is required, borates, quaternary ammonium compounds and other chemicals have found widespread application. For a variety of reasons, the use of CCA is not always considered desirable, and efforts aimed at developing alternative treatments have been undertaken.

One product area that has received increased attention in this regard is the borates. Borates have been used in wood preservation for almost sixty years. The first significant commercial use was in Australia for the treatment of hardwood lumber for protection from powder post beetles (*Lyctus spp.*) (Cummins and Wilson, 1936; Cummins, 1938 and 1939). In New Zealand, borate treatments for the protection of *Pinus radiata* building lumber from *Anobium punctatum*, have been used for many years (Bunn, 1974; Cross, 1992; Drysdale, 1994). In neither country has there been significant use of borate treatment for protection of building materials from termite attack. Following the many years of research with borate treatments outside of the U.S., interest in such treatments grew in the U.S. during the 1980's in a range of applications (Barnes et al, 1989), and these studies and other studies culminated in presentations at a conference in Nashville, TN in November 1990 (Williams, 1990; Williams and Mitchoff, 1990; Williams et al, 1990).

In recent years interest in the application of borates for the protection of interior lumber from termites led to initial above ground field studies (Preston et al, 1985 and 1986) with southern pine lumber as substrate, and these indicated that borates could provide protection to wood, although a borate retention level approximately eight times higher than that of the CCA controls was required to provide equivalent protection. A series of laboratory and later field test procedures have been published (Grace et al, 1992 and 1993; Grace and Yamamoto, 1993 and 1994; Tamashiro et al, 1991) on the study of the treatment and performance of borates in Douglas fir lumber against attack by Formosan termites. These particular studies generally concluded that retention levels of disodium octaborate tetrahydrate (DOT) around 1% weight/weight DOT could provide substantial protection against termite attack, although moderate and on-going feeding of the termites was noted. Tests in Queensland against *Coptotermes acinaciformis* initially led to the establishment of borate retentions around 0.5% wt/wt DOT, but these are under revision because of performance inadequacies at this level.

One difficulty encountered with research into the performance of wood preservatives against termites in various wood products is the lack of uniform standards for termite field test methodology. Ground contact stake tests are used throughout the world and at some sites the test results can encompass a termite protection component, but because of the usually over-riding presence of fungal degradation in ground contact situations, stake test results are not usually considered useful as indicators of product performance in situations where fungal attack is unlikely. Many different test methods to study termite degradation of wood products in structures have been used in those regions where such attack can occur. However, uniformity of approach, let alone uniformity of test methodology, is lacking. Differences in termite species, the termite hazard, termite behavior, use applications, wood species, etc. all have a bearing on this situation. An attempt to progress towards a more uniform approach was tried at the IRG conference in Kyoto in 1991 (French, 1991), but while this was a most useful forum, little progress has been made since then and this situation appears unlikely to change in the foreseeable future.

In our on-going studies, the methodology used involved a construction approximating the interior of a house structure, designed to provide a protected situation without exposure to liquid moisture. The roofs used provided wide eaves and were constructed from inert polymeric sheet material. Results are presented for the first of these studies involving several preservatives at multiple retentions. On-going studies in Australia and the U.S. are also described.

MATERIALS AND METHODS

Douglas fir lumber (50 x 100 x 2400 mm) was cut to lengths of 425, 525, and 600 mm. Four pieces of each length were cut from the 2400 mm long boards and these four matched pieces were then assigned to four different chemical treatment groups. Two replicate house units were used for each preservative/retention combination in the test.

Test samples were treated using a vacuum pressure cycle of 30 min vacuum at -80 kPa, pressure at 1050 kPa for 2.5 hours, and a final vacuum of 30 min at -80 kPa. The borate treatments were held in covered storage for 25 days after treatment to allow for diffusion prior to air-drying. All other treatment groups were air-dried under ambient conditions following treatment. Preservative treatments included CCA Type C (target retentions: 2.0 and 4.0 kg/m^3), disodium octaborate tetrahydrate (target retentions: 0.42% DOT, 0.84% DOT and 1.68% DOT), ACQ Type D (target retentions: 2.0, 4.0, and 6.4 kg/m^3) and deltamethrin (target retentions of 0.001 and 0.01 kg/m^3).

Each house unit consisted of 10 treated and two untreated Douglas-fir boards (Figure 1). The two untreated uprights were included to determine relative termite ingress and termite feeding activity. Untreated exterior grade Douglas fir plywood (600 x 600 x 10 mm) was used as siding. The roofs were constructed of 6 mm sheet high density polyethylene, natural color (white) 870 mm and 480 mm shortest slope using four matching isosceles triangles to give a peak height of 225 mm. Fabrication of the roofs was by a commercial plastics fabricator.

The units were constructed by fastening the lumber sections together using gang-nail strips (38 x 150 mm). In the on-going tests galvanized structural fasteners have been substituted for the gang-nail strips. The plywood siding was nailed to the framing lumber using galvanized nails with polymeric washers. Four nails were used on each edge of the plywood to provide a weather-tight structure. The units were then placed on a square array of four or six hollow decorative concrete blocks (100 x 200 x 400 mm) which had been placed flat side (wide face) on the ground to provide a hollow square base. Eight untreated pine stakes (12 x 12 x 300 mm) were placed in the ground inside each of the concrete block arrays both as a further indicator of termite activity and to encourage such activity. A roof was installed on each structure and was held in place without fasteners by its own weight (see Figure 2). At no time during the test period were the structures subject to ingress of water from rain, and moisture ingress through the block base appeared to be negligible. The Hilo site has a known high termite hazard from *Coptotermes formosanus.* The test was placed on an area of compacted volcanic rock of size ranging up to 25 mm diameter. Parts of the site had a very thin rocky soil covering. These conditions allowed rapid draining of water from rainfall.

Visual inspections were carried out at approximately 3 monthly intervals to determine the extent of termite feeding. After 51 weeks the units were disassembled and the lumber framing was rated visually and by probe inspection. Each sample was rated on a 0 to 4 scale with 0 being no attack and 4 being complete structural destruction. Intermediate ratings designated a continuum of attack between no attack (0) and complete loss of structural integrity (4). Termite activity in the plywood siding was observed but not rated. Attack was determined along with board ratings relative to treatment and retention. Ratings for the untreated samples included in each structure were also determined.

RESULTS AND DISCUSSION

Visual inspection results for each individual board within each simulated house test unit after 12 months exposure in Hilo, HI were recorded and Figures 3 to 5 show the scatter plot data for CCA Type C, disodium octaborate and ACQ Type D, respectively. Since two of the structures showed essentially no termite activity within the structure, on the untreated feeder stakes or on the plywood siding, the results from these two structures were treated as being non-determinant. Several regression models were evaluated to determine the fit of the data from non-linear regression analysis.

Termite activity was generally severe among the test structures. The two untreated control structures (24 boards) suffered very severe attack and little remained of the wood or plywood in these units after the 12 month test period. Similarly, in most of the structures with treated wood, the two untreated components included suffered severe termite damage, as did the plywood siding in most instances. In isolated instances with some all-heartwood untreated samples, only browsing by the termites was noted even in the presence of large numbers of termites, confirming that Douglas fir heartwood susceptibility to Formosan termites while generally high, does vary widely. Nevertheless, the damage to the untreated-only units during the 12 month test was essentially complete with an average rating of 3.6.

There was some tendency for attack to be more severe in the bottom plates than in the top plates, and this is presumably due to proximity to the ground from where the termites ascend into the structures. In the treatments reported here, attack on the untreated plywood siding was generally apparent. The lack of significant termite attack in two of the structures appeared to be due to site location rather than to any inherent properties of these treatments.

Large variations between mean retentions and actual individual board retentions as obtained by uptake data, were observed both within treatment groups and to a small extent between treatment groups. These differences between mean retention (both target and actual) and individual board retentions can be ascribed to the variation in heartwood content between boards and differences in heartwood penetrability. Such factors relating to chemical penetration into heartwood and variation in heartwood content also occur with commercial

Douglas-fir lumber treatments and contribute to high variations in retentions in commercial treatments, as well as treated wood performance, with Douglas-fir.

There was no evidence that moisture influenced the results of the test. No ingress of rain had occurred in any of the structures, nor did there appear to be any moisture movement into the bottom sill plate lumber in any instance. The wide eaves on the roofs of the structures provided ample protection from rainfall. Moisture content readings were taken on four test structures left in place from the test in May 1995. Moisture content of all boards in the structures were measured as well as that of the plywood siding. These measurements were taken shortly after a prolonged rainfall. Bottom plate moisture contents were 14-16% while top plate moisture contents were 13-15%. Moisture contents of the studs were 14-15% while the plywood siding gave moisture content readings of 19-20%.

CCA Type C treatment retentions were generally close to, if slightly above the targeted retention values for the two sets of treatments, providing mean oxide retentions of 2.2 kg/m^3 and 4.3 kg/m^3, respectively. Individual piece retentions ranged from 0.6 to 5.4 kg/m^3 among the four CCA structures, and such a spread of retentions was consistent with other treatment groups. In three of the four CCA structures covering the two target retentions, severe termite activity was noted on the untreated wood samples. In no instance was attack on the sapwood zone of treated samples observed. However, it is notable that in these unincised boards, no more than browsing (rating of 1) had occurred on any of the CCA treated samples at the completion of the test. This confirms our earlier findings in the above ground comparison tests reported in 1991 (Archer et al). On this basis, it is apparent that even in unincised lumber a CCA mean retention level of 4.0 kg/m^3 should provide generally good performance.

Three retentions of disodium octaborate tetrahydrate (DOT, commercially known as Timbor®, Polybor®, Hibor®) were included in the test. The borate treatment mean retentions were generally above that targeted and were 0.48%, 0.92 and 1.70% DOT wt/wt (2.2, 4.2 and 7.7 kg/m^3), respectively. One parameter noted with the borate treatments that was different from the other treatments reported here was that the termite attack was often noticed both in the treated sapwood and heartwood regions of the boards. As mentioned above, only one of the structures treated to 2.2 kg/m^3 DOT was determinant. This unit showed very severe attack with loss of wood structural integrity in virtually every sample. In the units treated to a mean retention of 4.2 kg/m^3 DOT, attack was more variable. However, in one of these units established attack was on-going in virtually all of the samples, although incongruously the two samples with the lowest retentions were the least attacked. Advanced structural damage was seen even at a board retention of 5.3 kg/m^3 DOT. In the third and highest retention group, in one unit severe structural damage was noted in a board treated to 6.2 kg/m^3 DOT while only browsing was noted in boards treated to higher retentions. In the other structure, while the boards treated to low retentions were severely degraded, it was notable that one sample board with a retention of 11.4 kg/m^3 also showed severe structural damage. These results show that at even high retentions, disodium octaborate treated Douglas fir lumber is prone to significant destructive termite attack.

In the ACQ Type D treatments, three retention groups were included. Mean retentions achieved were below group targets, being namely 1.6, 2.7 and 5.6 kg/m^3. Similar to the lowest retention group of borate treatments, only one of the lowest retention ACQ units was determinant. While most of the samples were subject to at most only browsing, one sample treated to 1.6 kg/m^3 was destroyed by termite attack indicating that this low retention of ACQ is inadequate for this application. In one of the units of the ACQ retention group with a mean retention of 2.7 kg/m^3, destruction was noted in one board with a retention of 2.4 kg/m^3, while in the other unit severe attack was observed up to a board retention of 3.7 kg/m^3. In the two structures treated with ACQ Type D to mean retentions of 5.6 kg/m^3, severe attack was only noted in samples at very low retentions of up to 1.3 kg/m^3, while boards treated to higher retentions than this were essentially untouched by the termites. Termite attack was not observed in the sapwood zones of any of the ACQ treated samples. In virtually every case where attack occurred, it was through penetration of a thin treatment zone in the heartwood into the untreated interior of the heartwood. Other studies using permeable *Pinus* species have shown that ACQ provides equivalent or superior performance to CCA against *Coptotermes* species in *Pinus* species. The data from this current study suggests that CCA Type C treatment provides greater repellency to the termites than is the case with ACQ Type D treatment, presumably due to the toxicity of the arsenic.

The four units treated with deltamethrin were not attacked by Formosan termites at the two retention levels used, that is 0.001 and 0.01 kg/m³. The lack of termite attack on these treated units was not due to lack of termite activity at the locale of these houses since adjacent units were severely attacked and the ground feeder stakes inside these units were also severely damaged. Furthermore, following the final inspection of the test reported here, some of these particular units were relocated to foundations of the untreated units in the test, and no termite activity was noted after another nine months exposure at these locations.

We attempted to fit several non-linear regression models to the data to allow comparisons of treatment performance. The data exhibited considerable variability and this prevented fitting a model with a high R squared value. Both negative exponential and logarithmic models were used. Using the exponential model, R^2 values of 0.89, 0.31 and 0.46 were obtained for CCA Type C, disodium octaborate and ACQ Type D, respectively. If in this analysis we arbitrarily assume that a termite rating of 0.5 represents a threshold level of essentially no attack, we can use the equation to determine the retention of preservative which controls termite activity. On this basis, the exponential model predicts threshold retentions of 0.5 kg/m³ for CCA Type C, 12 kg/m³ for disodium octaborate and 3.7 kg/m³ for ACQ Type D. With the logarithmic model and using a termite rating of 0.5 as the threshold level, a similar trend in results is obtained as in the exponential model. In this case the corresponding R^2 values for CCA Type C, disodium octaborate and ACQ Type D were 0.62, 0.37 and 0.48, respectively. The threshold values calculated from this equation yield 2.1 kg/m³ for CCA Type C, 27.2 kg/m³ for disodium octaborate and 4.0 kg/m³ for ACQ Type D.

As reported in an earlier study comparing CCA and borate treatments against Formosan termites in a protected above ground field test in Hilo (Preston et al, 1985, 1986), a similar relationship between retention and performance was seen in treatments using southern yellow pine as substrate. In that earlier field test over a two year exposure period, CCA Type C at a retention of 0.5 kg/m³ provided similar performance to borate at a retention of 3.8 kg/m³.

Highly variable performance of disodium octaborate treatment in Douglas fir in a field test against Formosan termite was also seen in an earlier study with diffusion treated Douglas fir (Archer et al, 1991). When the 2.5 year results of that trial were graphed for rating versus retention, a similar scatter and a similar retention/performance trend as noted in this current work could be observed. Analysis of the data from that study using individual exposure sample retentions, showed very little correlation between retention and the performance of disodium octaborate treatments up to the highest retention included (0.83% DOT) during the first two and a half years of the test. At that point only one of the CCA Type C samples showed even very light browsing by the termites. Furthermore, the mean retention of the CCA Type C samples was only 1.6 kg/m³ and both ends of the CCA treated samples were very poorly treated exposed cut faces. Interestingly, while the CCA Type C samples showed no further damage at the completion of the test (3 years exposure), all of the borate samples had been completely destroyed, along with the all of the untreated controls.

These studies show that the relative performance results of the treatments included in this current study are wholly predictable in the light of previous field studies where comparison control treatments have been used. The use of control treatments, as well as untreated controls, is the norm in wood preservative field testing throughout the world, in order to provide realistic comparisons between treatments in the control of expected biodeteriogens. As was the case with some previous studies into the use of borate treatments to protect Douglas fir lumber from attack by *Coptotermes formosanus*, when wood preservatives are tested solely against untreated controls overly optimistic predictions of product performance in service can occur. The results of this current study, however, confirm the results of other earlier studies which did include control treatments, and show the large difference in performance versus retention between CCA and disodium octaborate in protecting Douglas fir lumber in the interior of structures from attack by Formosan termites.

CONCLUSIONS

Field tests have been carried out using a simulated house structure to test the efficacy of preservative treatments under H1 and H2 conditions. These tests include radiata pine in Townsville, Queensland and Douglas fir in two studies in Hilo, Hawaii. The results of an initial test in Hilo for twelve months duration clearly demonstrate that this test methodology can provide a realistic evaluation of the termite resistance of treated unincised Douglas-fir lumber for house framing applications. The test differentiated between untreated and treated units and also among units treated with a range of preservatives and retentions. The results show that CCA Type C provides protection to unincised Douglas fir lumber at a relatively low mean retention. The results also confirm that a borate (DOT) retention of greater than 10 times that of CCA is required in order to provide equivalent protection from termite attack in this type of application, and this result is consistent with the findings of previous studies with these two treatments. The ACQ Type D results indicate that incising prior to treatment with ACQ Type D should be used in order to provide adequate protection for Douglas-fir heartwood for this application. Deltamethrin treatment showed complete inhibition of termite attack, even at retentions as low as 0.001 kg/m^3.

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Figure 1.

Test structure frame showing test members.

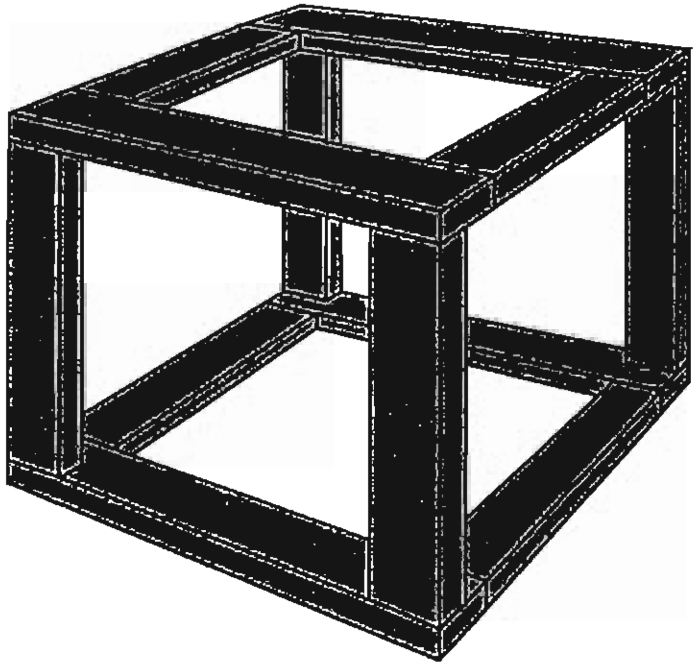


Figure 2.

Test structure layout, side view.

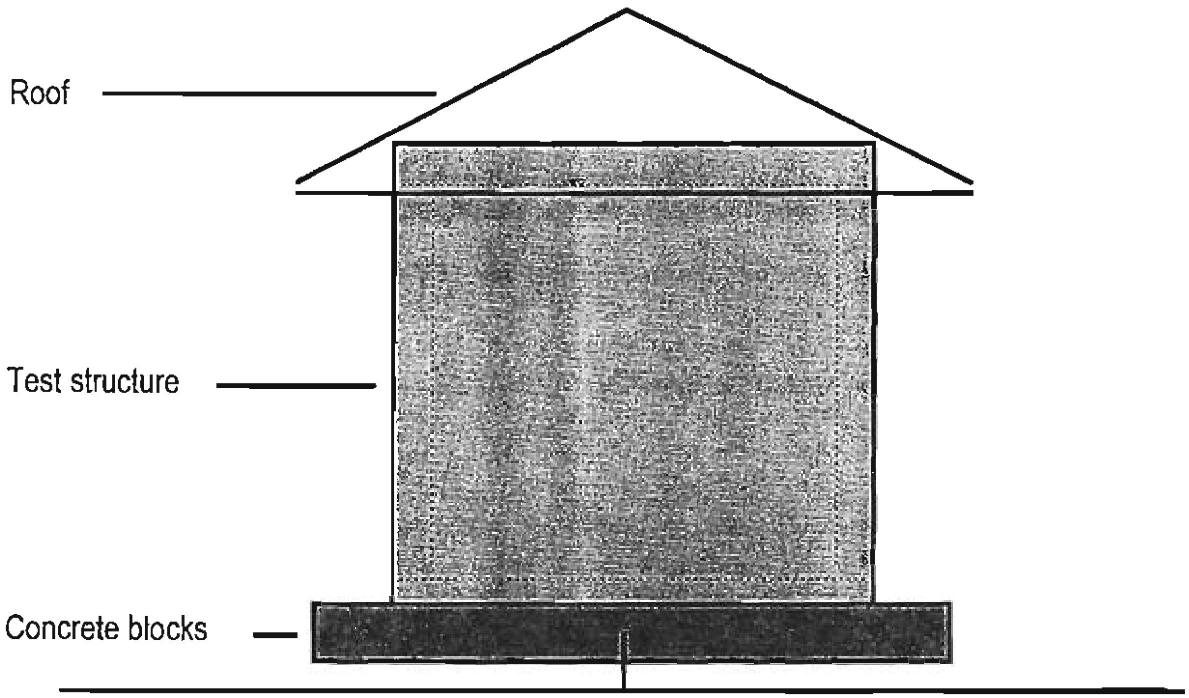


Figure 3.

Performance of CCA Type C samples versus retention.

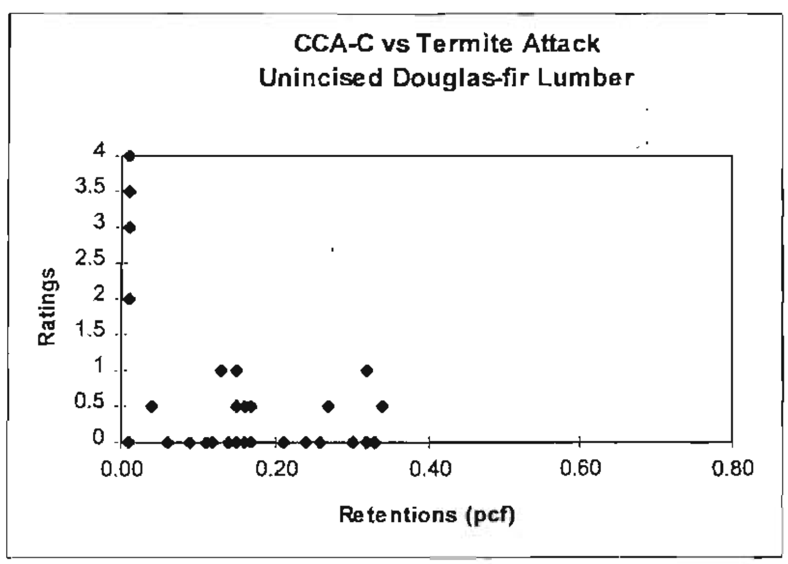


Figure 4.

Performance of Disodium octaborate samples versus retention.

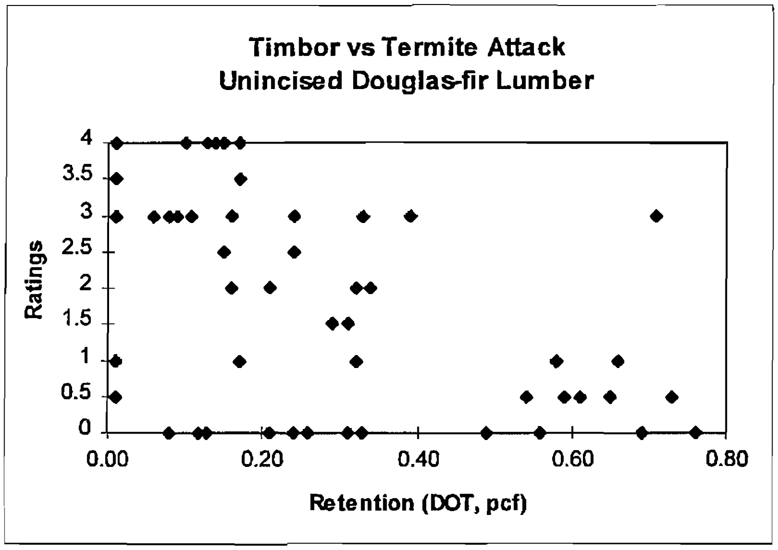
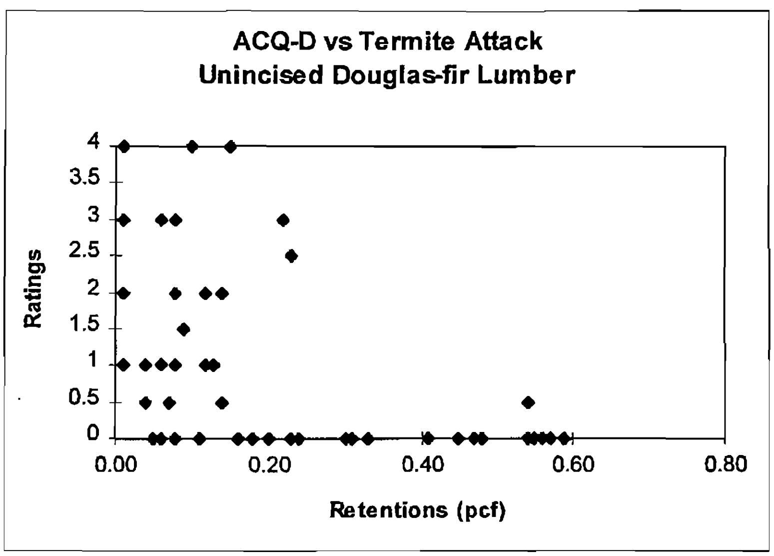


Figure 5.

Performance of ACQ Type D samples versus retention



FWPRDC PROJECT PN015.96

A RELIABILITY BASED DURABILITY DESIGN METHOD FOR TIMBER

- AN OVERVIEW -

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ABSTRACT

A reliability based durability design research project has commenced with support from the Forest and Wood Products Research and Development Corporation, the National Association of Forest Industries and participating research organisations. Stage 1 of the proposal is a four year research project with a total value of $3 million. The project commenced in Sept 1995 and measurable and useable results are now becoming available. The project is divided into four separate but interrelated sub-programs being, Model Development and Calibration, Environmental Agents - Maps and Databases,Testing and Assessment Protocols and Material Resistance. This paper presents a brief overview of the project and roles of the participating personell and organisations. Details of the individual sub-programs will be presented in following papers.

1.0 BACKGROUND

At the 23rd Forest Products Research Conference, the need to advance durability design was identified as a high priority of the timber industry (Mackenzie 1990). At the same conference, a "novel" procedure that considered durability design in a similar manner to structural design was proposed (Leicester and Barnacle 1990).

The challenge was taken up to develop a rational approach to durability design (Stringer 1993) using a reliability based procedure to determine residual strength and stiffnes of members subjected to decay, termites and physical degradation.

Early in 1994, the National Market Development Committee (NMDC) identified durability design as one of the major impediments to future timber use and utilization in Australia. A draft research and development proposal was subsequently developed by the Technical Advisory Group (TAG) for NMDC's consideration. It was based largely on earlier recommendations (Stringer 1993) with the thrust being to base durability design on reliability (probabilistic) principles as distinct from the existing prescriptive or deterministic methods which are rapidly becoming obsolete with respect to building regulations and user expectations and needs.

In 1994, three separate durability research proposals were developed and submitted to FWPRDC for funding. These submissions, which were unsuccessful provided the impetus to develop an integrated reliability based durability design research proprosal (Mackenzie 1995) for submission to the FWPRDC.

A two day workshop (researchers, industry, regulators and end users) was held in July 1995 to review and refine the proposal (Foliente 1995). This workshop was principally funded by the FWPRDC.

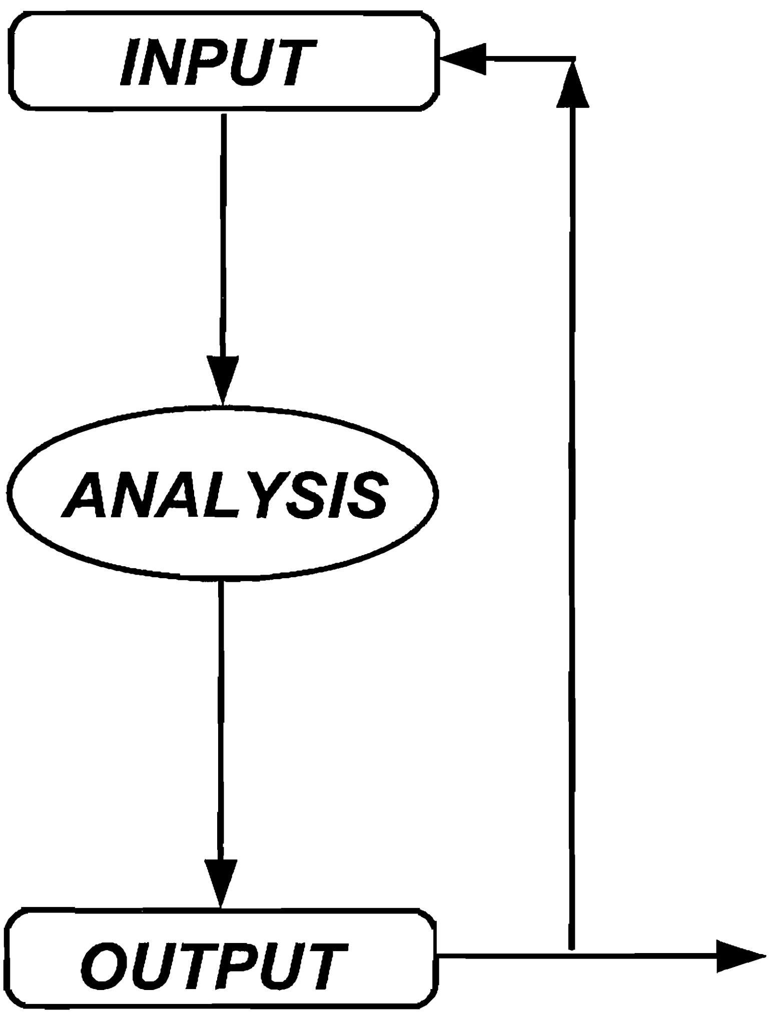
The NMDC subsequently endorsed the proposal and upon successful submission to the FWPRDC the Research Agreement was signed by all parties around December 1995.

2.0 THE VISION

The long term vision for this project is to develop user friendly computer aided design software that will enable the timber industries' customers to:-

- predict the life expectancy (or probability of failure) of timber used in any application within known or estimated degrees of certainty
- make informed decisions on important variables affecting timber durability and their influence on performance
- design and specify a durablity system for any use or application that will achieve their performance goals
- develop risk/cost management techniques with respect to new, replacement or maintenance of timber infrastructure

Figure 1 gives a "feeling" for how this proposed software may develop.



VARIABLES

Application, Location, Position, Species, Preservative treatment Supplementary protection, Maintenance regime,Performance requirements

Application of degradation models and analysis of risks associated with decay, termites, corrosion, borers etc.

Estimates of probability of failure ie:-
Strength P_r = 0.05 at 'x' years
Serviceability P_r = 0.2 at 'y' years
Aesthetics P_r = 0.5 at 'z' years
at a known confidence level.

Figure 1 "The Vision"

3.0 RESEARCH PROGRAM

The research program is divided into 4 interelated sub-programs. Figure 2 provides an overview of the overall project components and interactions.

3.1 Sub-Program 1: Model Development and Calibration

Leader: Dr R H Leicester (CSIRO-DBCE)
Principal Researchers: Dr R H Leicester, Dr G C Foliente (CSIRO-DBCE)

The sub-program includes model development, model calibration and development of a design methodology. Research includes field and laboratory trials to establish degradation actions and models and durability trials to validate the accuracy of model predictions. Field surveys (historical) will also be conducted to calibrate models developed.

3.2 Sub-Program 2: Environmental Agents - Maps and Databases

Leader: Dr I Cole (CSIRO-DBCE)
Principal Researchers: Dr I Cole, Dr J French (CSIRO-DFFP), Dr J Thornton and Dr G Johnson (CSIRO-DFFP) and Mr M Cause (DPI-QLD)

This includes determining the level of risk of the various hazards and includes "mapping" of termite and other insects, in and above ground decay, corrosion and glue degradation agents. Information will be gathered on a macro scale related to climate, existing field trials, anecdotal evidence and hard historical data. A micro climate data base will also be developed for a typical range of building types and applications and these in-turn used to modify in-service conditions.

3.3 Sub Program 3a: Protocols

Leader: Dr J Thornton
Principal Researchers: Dr J Thornton, Dr G Johnson, Dr I Cole and Mr M Cause

This part of the project has a high priority to develop standardised techniques and assessment methods for material resistance with respect to termites, decay and corrosion. Included in the research are establishment trials using accelerated field simulation laboratory techniques for termites, fungi and corrosion.

3.4 Sub Program 3b: Material Resistance

Leader: Dr J Thornton
Principal Researchers: Dr J Thornton, Mr D Gardner (SF-NSW), Dr G Johnson, Dr I Cole, Mr M Cause

This sub-program is primarily concerned with determination of material resistance and rating resistance in a form that is compatible with probabilistic modelling. It will also involve calibrating historical resistance index properties to new test data generated under Sub-Program 1. Existing in-ground and above ground field trials are being supported together with new trials that have been established to study corrosion, glued products, treated timber, weathering and termite resistance.

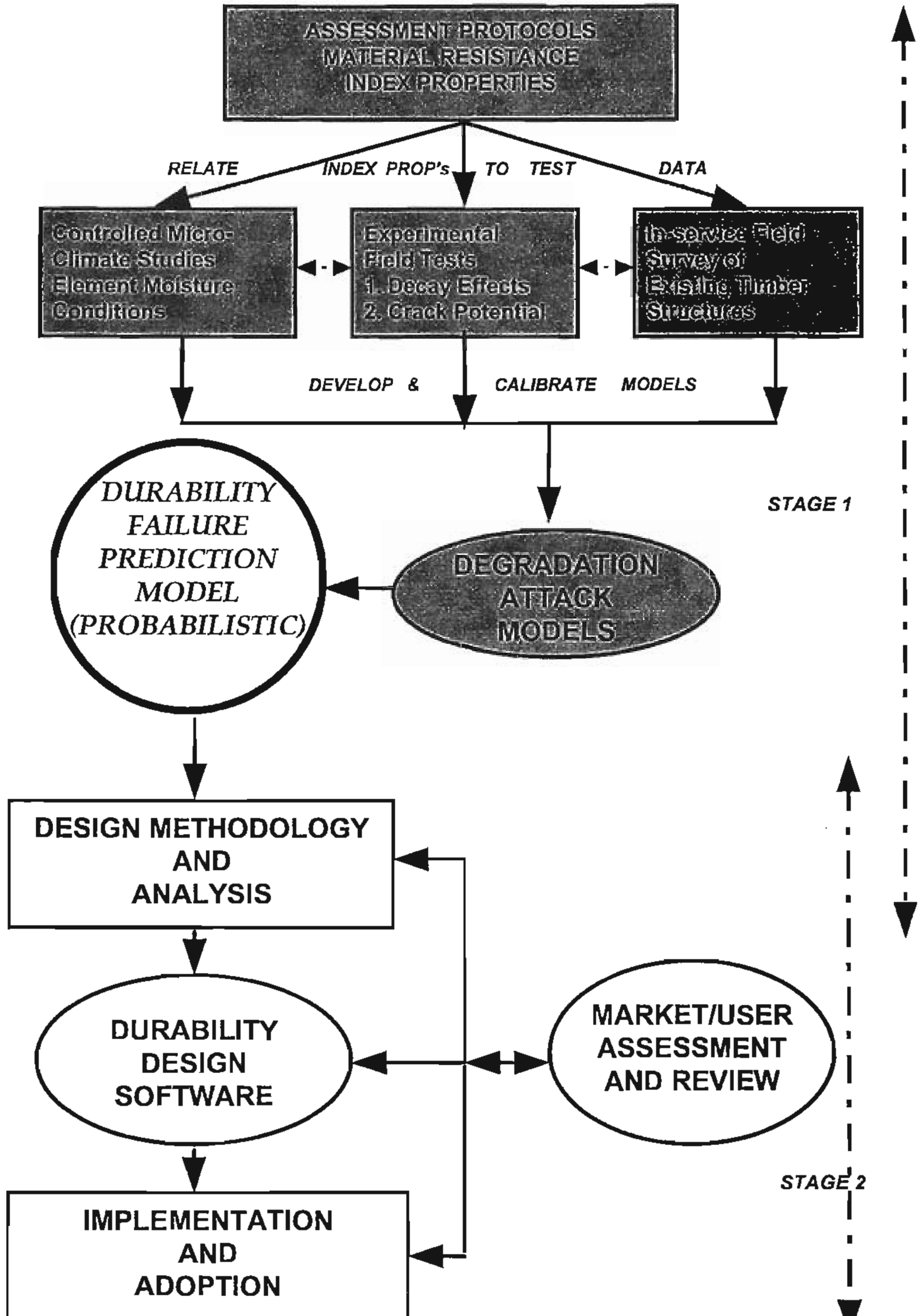


Figure 2 Project Overview

4.0 METHODOLOGY

4.1 Model Development

The methodology being adopted in this project is directed at obtaining data that can be input into probabilistic failure prediction equations in a form such as the following for strength:-

$$P_f = f(\sigma, t, D_1, D_2, D_3, \text{etc})$$

Where P_f = probability of failure
f = function
σ = level of stress
t = time
D_1, D_2, D_3, etc = material resistance properties, hazard levels, human factors etc

Similar equations are applicable to serviceability and functional requirements, such as aesthetics, for relevant applications.

For each of these performance requirements, sub-models will be developed to predict loss of strength or serviceability for other factors such as termites, decay, corrosion etc. These may typically be depicted as shown in Figure 3.

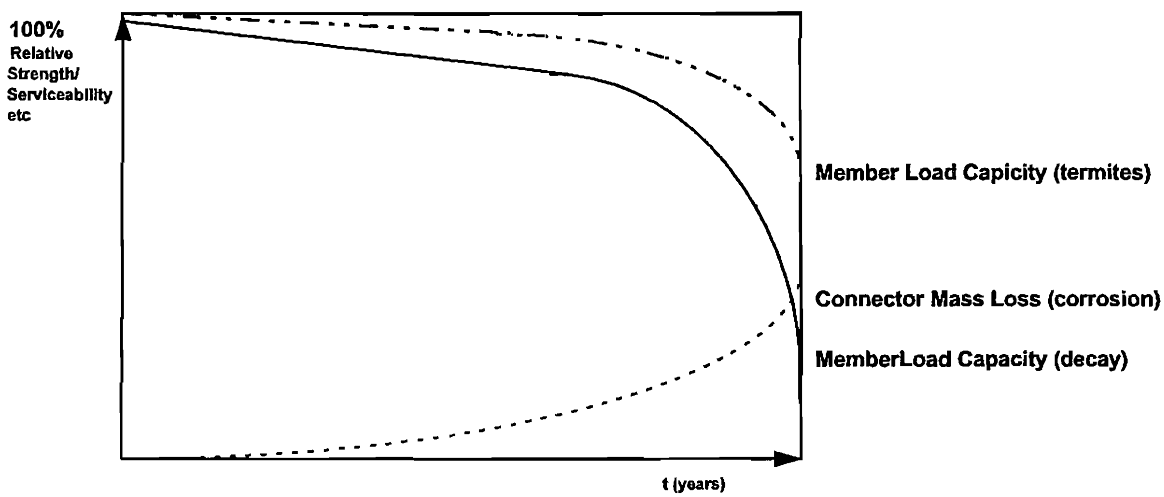


Figure 3 Typical Time/Degradation Curves

4.2.1 Model Development - Experimental Program

This consists of laboratory and field studies comprising three main components:-

- **Microclimate Effects**
  - controlled conditions, geometry/moisture/temperature
  - potential for hazard attack
  - linked to index properties
- **Field Tests**
  - full size specimens
  - specific key site locations
  - linked to index properties for model calibration
  - effect of decay on strength and stiffness determined
  - in-service performance determined for cross-arms

- **In-Service Field Surveys**
  - typical applications selected
  - durability assessment of components conducted
  - related to climatic and micro-climatic conditions and hazards
  - used to calibrate models

4.2 Quantification of Hazards

Hazard maps based on levels of risk will be developed for termites, above and in-ground decay, corrosion and micro-climate building influences. To achieve this, existing and new experimental studies have been initiated. Where possible, these studies link together the historical climatic conditions at the various "Index" property sites throughout Australia with the new studies.

4.2.1 Termite Risk Assessment

A national termite risk survey has been initiated via the CSIRO Double Helix Club. It is hoped this will generate around 20,000 data points (randomly surveyed houses) detailing the incidence and nature of termite damage with respect to the characteristics of each house.

This initial survey will be complimented by targeted surveys of the pest control industry, building authorities and other knowledable industry sectors. All data obtained will be statistically validated, analysed and computer generated maps produced.

4.2.2 Above Ground Decay Hazard

Data is being derived from existing above ground "L" joint trials established in 1987 at 11 sites across Eastern Australia. In addition, a limited replicate set of new "L" joint trials has been installed to gain a better balance of climatic variation. These trials are also being complimented by further new above ground trials using CCA treated pine and refurbishment of the CSIRO "Climatic Index Test" sites. all data derived will be analysed and calibrated against the field tests, surveys and the known historical performance of data obtained from 4.1 above.

Above ground moisture/temperature data will be logged at Key Index sites and this will be integrated with the decay score data derived and the national meteorological data base to produce above ground decay risk hazard maps. Preliminary maps have been produced using Scheffer's Index although modification of this would appear necessary to obtain satisfactory correlations for Australia.

4.2.3 In-Ground Decay Hazard

As in 'above ground decay hazard'. existing in-ground graveyard trials for natural durability continue to be monitored to produce decay/termite degradation rates for 'Key' Index sites across Australia. New trials at 27 sites have also been established for untreated timber (except for insecticidal treatment) using radiata pine, as well as 5 sites for CCA treated radiata pine.

Moisture/temperature data will be logged at 'key' sites and this will be integrated with soil/meteorological data to produce in-ground decay risk hazard maps.

4.2.4 Joint Degradation Hazards and Indices

This component comprises both glued and mechanically fastened joints and concentrates on establishing and quantifying the characteristics most likely to affect performance including micro-climatic (temperature humidity, moisture content) and environmental (salt deposition) influences. Seven 'key' experimental sites have been selected and buildings monitored to reflect the typical range of macro and micro climatic conditions experienced across Australia.
Wherever possible, these have also been tied to the 'key' sites selected for above and inground trials described above. Maps and Indices will be produced to quantify the level of hazard or risk relevant to corrosion and glued joints with respect to both macro and micro climate and environmental conditions.

4.2.5 Micro-climatic Data Base

Existing climatic data bases will be coupled with micro-climatic data being obtained from experimental monitoring of houses at 6 locations across Eastern Australia. Again 'Key' locations have been chosen. Parametric models connecting external climate to roof, wall and sub-floor spaces in buildings will be developed that permit estimation of surface and sub-surface moisture content in timber members. Degradation parameters will also be developed as a function of EMC to enable exposure test data to be integrated into mapping and modelling.

4.3 Material Resistance

A fundamental requirement of developing a probabilistic durability design method involves the reliable prediction of a materials resistance to various hazards. This part of the research is concerned firstly with developing standardised testing and assessment protocols (preferably accelerated techniques) and secondly, establishing from existing and new trials and experiments, material resistance and rates of deterioration versus loss of capacity or serviceability.

4.3.1 Protocols

Testing and assessment protocols are being developed for the following:-

- **Termites**
  - accelerated laboratory field simulation using imported colonies
  - alternative techniques may be included in Stage 2 or developed independently such as the CSIRO/QDPI lunch box and field frame techniques
- **Decay**
  - existing in-ground and above ground protocols will be reviewed to determine the most suitable methods for standardisation
  - field methods as well as accelerated laboratory techniques will be established
  - relative and absolute decay resistance will be considered for both treated and untreated timber
- **Corrosion**
  - accelerated laboratory and chanber test methods are being developed
  - EMC, surface moisture, salt deposition and mass loss are targeted
  - comparative field studies are being conducted to verify laboratory methods.

4.3.2 Material Resistance

- **In-ground Decay and Termite Resistance**
  Existing CSIRO field trials were inspected at 27 years and decay rates (mm/year) established for the heartwood of 77 species using first quartile and mean quartile specimen life. These trials will be re-inspected and reported at 29 years. Data will be coupled with previous rates of deterioration or other species. A new field trial has been established using a range of levels of CCA treated radiata pine at five 'key' sites in Eastern Australia. These in-ground trials are also complimented by matching AFS specimens to enable correlations between laboratory and field tests to be determined.
- **Above Ground Decay**
  As noted in 4.2.2 above, existing and new "L" joint tests and new above ground decking tests have been established. A 7 year assessment and report of the "L" joints has been produced giving decay scores and the 9 year assessment commenced. Data obtained will be coupled with historical performance and field survey data and after calibration, input into the model. The trials should extend beyond the life of Stage 1 of the project.
- **Corrosion**
  Field and laboratory trials have been established to determine corrosion rates for a range of standard metal connectors, nails etc and treated and untreated timber. A range of common fasteners will be structurally assessed at various degrees of corrosion and loss of capacity will be input to the model.

5.0 CONCLUSION

This is a "world first" project that combines skills and knowledge across at least five scientific and engineering fields. The project is now a little over 12 months into its 4 year time frame. The level of enthusiasm and co-operation between all the research organisations involved demonstrates the value of integrated research that is initiated and supported by industry. As will be noted from the following more detailed papers presented on the four Sub-Programs, useable, valuable results are starting to be achieved. If the project achieves its long term objectives, durability design in timber will be on a 'plane' above that of competitive materials and this will restore our user's confidence in our material.

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DIRECTIONS FOR FOREST PRODUCTS RESEARCH IN AUSTRALIA

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INTRODUCTION

Investment in research and development in Australia is low compared to the OECD average, particularly in the forest and wood products sectors. Gross Expenditure on R&D in Australia has increased in recent years, but SCOREBOARD '95 (compiled by Coopers and Lybrand for the Commonwealth Industry R&D Board) still puts Australia 18th on the global list of investors in R&D.

Turner and Lambert (1996 unpublished) estimate that investment in forest and forest products research in Australia has increased by 3.1% (forest) and 2.7% (forest products) per annum over the last five years, without adjustment for CPI. In real terms this is a decrease, compared to an overall increase in research investment in general (SCOREBOARD '95).

The direct impact of the level of investment in research is difficult to quantify, but it is generally accepted that effective research contributes significantly to the economic and social well being of a country. On that basis it is important to maximise the return from research investment in the forest and wood products industry in Australia. Increased investment will not occur unless tangible returns can be demonstrated to potential investors.

This paper looks at the framework that is needed to maximise the effectiveness of research. Although it is in the Structural Applications section of the conference, the issues raised refer to investment in all sectors of the forest and wood products industry in Australia. The paper uses industry as an example but the concepts are equally applicable to research for community and national benefit.

The paper does not identify areas for future research, but looks at the more fundamental question of the framework in which research directions are determined. If the framework is in place, whether it be in a country, an industry sector or a nation, then research priorities will be meaningful and focused on a predestined end point, providing maximum opportunity for practical application of research results.

In many organisations and sectors, this framework is missing and research investment fails to provide the expected return.

INNOVATION AND RESEARCH - who needs it

A number of people have questioned the need for increased research effort in the industry. This is despite the fact that much of the fabric of everyday life is the result of research undertaken in the past eg electricity, transport, telephone, photocopiers and manufacturing equipment etc- the list is endless. **EVERYONE benefits from research.**

Anyone who looks around them at "successful" companies and countries is likely to identify characteristics such as innovativeness, forward looking, identifying markets, and being first. All of these things are generally backed by good information which has been obtained and carefully analysed through research.

Innovation is the means by which an industry, company or community maintains and develops its competitive edge and economic/social growth. Research occurs on a continuum from concept to the commercial adoption of an innovation. Although there are more traditional definitions which categorise innovation into the stages of research, development, demonstration and technology transfer, these are all integral components of research, which should be viewed as the gaining of the knowledge required to bring a concept through the continuum to commercial/practical adoption. Therefore research is not only something for the laboratory but is an essential tool for every growing business and much of it can be undertaken "in-house" on the factory floor.

Although research is recognised as an essential tool to assist industry become and remain competitive through innovation, Australian industry has traditionally been below the OECD average in its investment in research.

In addition there has frequently been a mismatch between the research undertaken by public organisations and its relevance to Australian industry. This has resulted in some exceptionally good science and some clever innovations which have not been adopted commercially. One of the reasons is that researchers and industry end users often have different perceptions of research priorities. This has been perpetuated to some degree by the traditional view of technology transfer as something which occurs after the research has been completed.

There is growing recognition that technology transfer is not a separate activity but has the highest potential for success when the researchers and end users of the research work together to develop the research project and to implement the results. Mechanisms have been developed to increase the interaction between public research organisations and industry. The R&D Corporations, the Cooperative Research Centres and the requirement for CSIRO to obtain 30% external funding are examples of current efforts to increase the level, relevance and effectiveness of industry research in Australia. These initiatives are designed to link industry and publicly funded research organisations to invest in research that will increase the innovativeness, competitiveness and growth of Australian industry.

Research is a tool for use by industry and the community to assist it to reach its goals for the future. Innovation and the development of better and cheaper ways of doing things are the key to success. The basis for this innovation is research - hence the relevance and need for research in every growing organisation.

To summarise, innovation is generally based on research and if looked at outside the normal narrow focus of "technical" research, has the following characteristics:

- Innovation is a tool which can assist an industry or company to maintain and develop its competitive edge and economic growth.
- Research occurs on a continuum from concept to the commercial adoption of an innovation.
- Research is the gaining of the knowledge required to bring a concept through the continuum to commercial adoption. Therefore research is not only something for the laboratory but is an essential tool for every growing business and much of it can be undertaken "in-house" on the factory floor
- There has frequently been a mismatch between the research undertaken by public research organisations and its relevance to Australian industry. This has resulted in some exceptionally good science and some clever innovations which have not been adopted commercially.
- There is growing recognition that technology transfer is not a separate activity but has the highest potential for success when the researchers and end users of the research work together to develop the research project and to implement the results.

DEVELOPMENT OF THE FRAMEWORK

To use the research tool most effectively an industry, company or community needs to have a vision for its future in the next 2, 5, 10 and 20 years and then assess the research that is needed to achieve that vision.

Research is not a topic that can be considered in isolation. It must be an integral part of a larger vision for the people who will use the research results in practical applications.

From an industry perspective, there is a hierarchy which includes a global perspective, a national perspective, an industry sector perspective and a company perspective. In an ideal world, these all form part of a feed-back loop, continually being modified and adapted as changes in the dynamic world occur.

This dynamic change and modification of the vision is often used as a reason why research cannot "fit". The argument is based on the long term nature of research. However, if research is seen as tool to assist with the implementation of a vision, the research itself becomes a dynamic element and requires proper planning, project management, and regular review with "go" "no-go" points at regular intervals.

If the vision changes and therefore the research needs, there is no sense in continuing a particular research direction.

Industry associations can play a key role in assisting in the development of the vision at the national, sector and company levels by taking a lead in the development of the sector vision, and having input to national industry development strategies. By definition these associations then have a major role in developing the research framework in which public research organisations and pooled fund investors (such as RDCs) can establish effective programs.

OPTIONS FOR INVESTMENT IN RESEARCH

Once the vision has been determined and the research needs identified within that vision, there are a number of options for investment in research. These include:

- **Import Technology/Information** - this is appropriate in some cases, but there will always be a downside; additional work is generally required to install and adapt the system to Australian conditions; when expansion is required, the technical expertise is not readily available and can be expensive to buy in. In addition, this method allows the user to "keep up" but not necessarily to be ahead.
- **Import research from overseas** - ie contract providers from other countries;
- **In-house research** - this is the preferred option if the intellectual property will give the organisation a major competitive advantage
- **Contract out** - this is dependent on the required expertise being available when it is needed
- **Pooling resources** to undertake research of common interest eg through an R&D Corporation or CRC

The ideal solution is a mixture of these options, depending on the needs of the organisation. In the future, scarce resources (both financial and skill based) are likely to result in an increased use of pooled funds, but with a highly focused investor/end user driven objective, rather than the more traditional "general grant" approach.

Similarly there may be an increase in contracting out research to specialist research providers, both public and private, which have highly skilled experts in specialised fields. This provides an opportunity and a challenge to Australia's publicly funded research organisations to provide an outcome oriented service to companies and industry groups, on a joint venture basis.

For this to be successful, there must be a greater emphasis placed on the cost-effectiveness, timeliness, quality and relevance of the research, and recognition that a contract must be adhered to. In many cases the contract is signed by Management in an organisation and the researchers have no idea what obligations have been agreed on their behalf.

ISSUES

We invest in research as a tool to help increase economic and social well being. If this is the case, why is it so difficult to encourage people to invest?

There are a number of impediments to investment in research many of which result from a mismatch between the objectives of the people doing the research and those who want to use the results in a practical application.

Investment dollars

One of the other key impediments is lack of dollars. Reasons for this include:

- time between investment and return
- need to maximise shareholders return in the short term
- industry uncertainty as to whether research organisations can deliver, in terms of cost effectiveness, timeliness and provision of a commercially acceptable product
- concentration by research providers on longer term issues rather than short term solutions
- disagreement over ownership of intellectual property
- changing tax regimes, removing the long term certainty required
- a history in Australia of government funded research
- uncertainty of resource availability
- industry downturn
- corporatisation of State forest agencies and an associated downturn in research investment

Investment in research is one of the more difficult areas to adjust during periods of tight cashflow, because of the long term commitment required. This contributes to the reluctance of organisations to invest. As organisations become more conscious of the need for a return on the investment within a given time frame, the longer term, higher risk projects go by the wayside.

Intellectual Property (IP)

Ownership and control of IP is one of the key impediments to collaborative research. More energy is put into trying to define ownership, liability for costs of IP protection, and licensing arrangements than any other part of a research agreement, particularly if there are a number of parties involved in funding and implementing the research.

It is essential that this occurs before the agreement is finalised, as disagreement at a later stage can seriously affect the final value of the research results.

Management of IP is a complex issue Investors, researchers and other parties have a responsibility to ensure that research outcomes (IP) are adopted, by converting them to products, processes and services for commercial use in the industry they represent. This raises a number of issues about the most effective way to achieve that objective in terms of management, ownership and protection of that IP, and an individual solution must be reached for each project to maximise the return on investment to the industry and the community.

Commercial failure of research outcomes

Technical excellence is only one component of effective research. A Workshop held jointly by the Research and Development Corporations in October 1995 identified some of the many reasons for commercial failure of research outcomes which are technically sound. These include:

- not commercially viable - ROI too low or too slow for commercial investment
- not enough capital - risk too high
- a combination factors which, when occurring together, can cause failure if not properly managed:
  - ⇒ excitement
  - ⇒ ego
  - ⇒ emotion combined with
  - ⇒ obvious industry benefit
  - ⇒ available funds; and
  - ⇒ inadequate control and no avenue for independent assessment of progress
- size of Australian industry versus the scale of technology and cost of commercialisation
- attitude of researchers -
  - ⇒ publishing is more important than investment in projects with good commercial potential and the incentive to take them beyond the laboratory (this has been partly due to a promotion system within research organisations based on international peer recognition rather than practical benefits provided by the research).
  - ⇒ looking for quantum leaps rather than incremental growth - industry prefers the latter, researchers the former

The RDC workshop also identified a number of things which must be kept in mind, to increase the chance of successful research outcome. These include:

- developing research priorities within the framework of the broader industry/company vision
- ensuring there is a market before you start - there is no point trying to derive a financial return or force commercial adoption if there is no market
- developing a business plan which includes a route to market, with commercial partners involved early in the project (as financial contributors if possible)
- understanding:
  - ⇒ markets for the IP (or research outcomes)
  - ⇒ business paradigms involved
  - ⇒ the need to develop and manage the implementation of the commercialisation strategy
- at the outset of a project, analysing the market, defining the need, preparing a broad specification of what will be produced, productivity rates, market penetration and ROI.

Lastly, as noted before, it is important to ensure that all the conditions relating to IP management and ROI are included in the Research Agreement before the project starts - otherwise the chances of success are greatly diminished.

WHERE TO FROM HERE

To maximise the benefits from research in the future there needs to be increasing mixing interaction between industry (users of research results) and research organisations so that the best expertise can be used. Although some competition between research organisations is valuable, Australia does not have the resources to support a large number of centres, and we may be better to invest in centres of excellence which can attract internationally recognised researchers. In addition:

- public research organisations will become more focused on contract research in specialist areas - the success of this will depend on their ability to deliver in a timely and cost-effective manner
- more effort will need to be placed on the commercial implementation of research results. This will mean that a project does not end when the experimental phase is complete, but may require the researchers to work within organisations to assist with the implementation phase
- industry organisations will take a more active role in identifying generic/collaborative research outcomes required to enable the sector to achieve its broader vision - pooled R&D funds will be used
- R&D corporations will take on a role of "broker", putting together consortia of industry, government, researchers and other organisations to share the cost and benefits of specific research.

Five point plan

For this to occur most effectively, a simple five point plan is required.

1. Vision

Before undertaking any research, the investors, research providers and beneficiaries must be clear as to **why** the research is being undertaken, **who** is going to use the results and what the mechanism is likely to be for that application to occur - there must be a vision which clearly identifies the need for a particular line of research.

This fundamental principle still applies whether the research is of a fundamental and long term nature, or whether it is to find an immediate solution. If the questions **"why", "who" and "how"** cannot be answered, the project should not proceed.

2. "Business" Plan

The research should fit into an overall business development (or community development) strategy with a clearly defined "business" plan. Research is no different from any other business activity. It requires investment that demands a return. That return may include direct financial or non monetary benefits such as improved profit, better services, improved environment and greater employment opportunities.

Before starting, each stage of the project must be planned and costed so that the investors have a tangible cost/benefit budget on which to make their decision. We often hear the view that research is different and that you cannot determine the precise investment and return that will result. This might be true, but if there is not a carefully thought out plan to begin with, investors will not be able to decide how far they are prepared to go to arrive at the desired outcome. Plans can be varied along the way, but only if positive outcomes can be demonstrated within a reasonable time frame, and the project still reflects the overall vision which identified the need in the first place.

3. Multidisciplinary approach

Technical research is only one component of the research process. A number of other skills are required to ensure that maximum return on investment is obtained. For example:

- legal input ensures that intellectual property is properly dealt with from the beginning of a project,

- financial input ensures that realistic budget estimates have been made and investment decisions are made on best estimates of return,
- end user input ensures that the project objectives are relevant to the needs of the user and are being developed in a cost-effective and commercially viable manner
- management input is required to ensure that a proper business plan has been developed, realistic, output oriented milestones are in place and an effective progress monitoring and quality assurance system has been developed.

4. **Contractual Obligations**

Where the research is being undertaken as part of a contract, the research provider must ensure that high quality product is delivered in a timely and cost-effective manner.

When accepting contracts to undertake research, providers must recognise that it is **a contract** for provision of services of a given quality within a given time. This is particularly important where there are a number of parties, as the reputation of the research provider will depend more and more on the quality of the research **AND** the timeliness of the outcome. Delays due to other organisational commitments will not be acceptable. Organisations will also have to recognise that contracts to provide services (and thereby bring external income) must be fulfilled as **first priority.**

5. **Feed-back**

The Business Plan should include provision for regular feedback from the multidisciplinary team the ensure the project is still on target to meet its original (or amended) objectives. The questions should be continually asked "why", "who", "how".

THE EVALUATION OF STRUCTURAL ADHESIVES

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SUMMARY

The increasing use of adhesive bonding technology in structural timber underlines the need for an adhesive evaluation standard; the alternative is to retain or existing prescriptive standards and stagnant adhesive technology. In Europe a project has begun[1] to develop a performance based CEN Standard for wood adhesive evaluation. This paper reviews the rationale which might underpin an adhesive evaluation standard with a view to developing a parallel AS / NZS standard.

1 INTRODUCTION

In Europe there is a project in place to develop a CEN Standard for adhesive evaluation to assist in the introduction of new adhesive bonding technology to the timber industry. In Australia, the need to develop adhesive evaluation procedures is even more acute than it is in Europe. It arises out of our inability to effectively bond higher density native hardwoods with phenolic adhesives. In both glulam and finger jointed timber the difficulties are especially acute within the finger joints and, in glulam, even the face joints of higher density species present problems. Our inability to bond high density / high strength eucalypt species with phenolics and the lack of a methodology to evaluate wood adhesives leaves the hardwood sector with little or no room for manoeuvre.

The measurement of short term strength of any structural material is a relatively trivial exercise; ensuring that products retain predictable strength levels in the longer term is more difficult. However, there is an expectation that the Building Code of Australia will eventually follow a NZ lead and require that designers provide for a life cycle of 50 years.

2 RELIABILITY BASICS

The adoption of adhesive screening methodologies must carry with it an implication that any adhesives bonded product will have the required structural reliability characteristics. In connection with wood adhesives the following factors affect reliability.

Service Environment and Chemical Degradation

Not all structural products have the capacity to function satisfactorily in all service environments. Wood products, for instance, do not function satisfactorily as refractories nor is that expected of them. At extreme temperatures wood simply undergoes chemical change which renders it useless for that purpose. Thus our

[1] The Swedish National Testing and Research Institute is coordinating the project.

definition of reliability is inextricably linked to the service environment and user expectations which are not always easy to define. Under AS/NZS 4364:1996[2] the following adhesive type definitions were introduced.

Table 1: Summary of adhesive types given in AS/NZS 4364:1996.

Temperature	Climatic equivalent to (1)	Examples	Adhesive type
> 50°C	Not specified	Prolonged exposure to high temperature	I
≤ 50°C	> 85% r.h. at 20°C	Full exposure to the weather	I
	≤ 85% r.h. at 20°C	Heated and ventilated building. Exterior protected from the weather. Short periods of exposure to the weather.	II

(1) 85% r.h.at 20°C will result in a moisture content of approximately 20% in softwoods and most hardwoods, and a somewhat lower moisture content in wood-based panels.

In AS/NZS 1491:1996 Service Class definitions are provided; see Table 2.

Table 2: Summary of AS/NZS 1491 Service Class definitions and adhesive requirements.

Service Class	Environment	Expected Wood mc	Adhesive type specified
1	20°C r.h. 65% except for a few weeks each year	< 12%	I or II
2	20°C r.h. 85% except for a few weeks each year	< 20%	I or II
3	mc greater than Service Class 2 or full exterior exposure	> 20%	II

Applied and Induced Stresses

Applied and induced stresses affect the reliability of many structural materials, eg, fatigue of metals. In evaluating adhesives, the possibility that degradation can be caused by cyclic stresses in particular cannot be ruled out. Any screen tests have to at least acknowledge this possibility.

Interaction of Factors

Where chemical degradation takes place it is usually a highly localised phenomenon, chemical reaction occurs at the molecular level. Thus, if an adhesive hydrolyses, the localised wood moisture content affects the kinetic rate. Because of the slow rate of moisture diffusion, the innermost parts of adhesive bonded products will be less affected by moisture cycling than the outermost parts. A crack initiated by applied or induced stress might also provide a moisture path which accelerates adhesive bond degradation. Accordingly, the loss of bond strength is an extremely complex phenomenon involving the interaction of many factors.

[2] AS/NZS 4364:1996 Adhesives, phenolic and aminoplastic, for load-bearing timber structures—Classification and performance requirements

3 ADHESIVE CHEMICAL DETERIORATION

Chemical degradation is rightly and widely held to be the primary reason for wood adhesive degradation. At present, timber standards for both finger timber and structural glulam simply prescribe the permissible adhesives for given service conditions. Clearly, it is widely accepted that, in situations where man would choose to use adhesive bonded wood products, the reaction of adhesives with diffused water is the major cause of chemical degradation. Chemical reaction rates belong to the field of chemical kinetics.

3.1 Chemical Kinetics

ASTM D4502 details test procedures are described based on the principles of chemical kinetics. These have the advantage that they also provide a basis for a degradation model which can be used later in structural reliability evaluations. Under this method, block shear specimens bonded by the target adhesive and controls are placed in both a fully saturated and completely dry environment at elevated temperatures. Specimens are removed at time intervals over periods ranging up to 130 days and subjected to block shear strength measurements. If the kinetic model holds true, then the strength degradation can be described by an expression of the form

$$(\tau/\tau_0)=e^{-kt} \qquad 1$$

where τ = adhesive strength at time t, τ_0 = shear strength at time t = 0, k = rate constant which depends on the temperature and local wood moisture content = $\alpha e^{-\beta/T}$, α, β = constants to be determined by experiment, T = local wood temperature in °K. The method holds the rh and temperature for a sufficient period for the wood moisture to be constant throughout the relatively small block shear specimen. To apply this model to a large glulam member to compute strength degradation requires knowledge of both the moisture and temperature distribution point to point within a member. Thus the technique is not directly applicable to estimating the degradation in strength of a large glulam member. Furthermore, the method does not contain any requirement for the specimens to be loaded during the degradation nor is any attempt made to separate the adhesive strength from that of the shear strength of the adjacent wood. This causes considerable scatter of experimental results.

Limited experience is available at Monash in applying a modified form of this method to UF bonded Mountain Ash. Both modified block shear (which measures shear strength) and tapered cantilever specimens to ASTM D3433, see Fig 1, (which measures cleavage strength) were prepared and aged under the conditions detailed in Table 3. The block shear specimens involved end grain bonding to eliminate wood failure. The grain direction in the tapered cantilever specimens was also arranged to avoid wood failure, fig 3. The elimination of wood failure has the advantage of reducing experimental scatter as wood failure data is not intermingled with bond failure data. It has the disadvantage in the block shear specimens that end grain bonding is atypical although the effect is less pronounced in the case of tapered cantilever specimens.

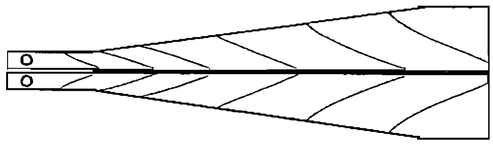

Fig 1 Doubly tapered cantilever specimens used for cleavage testing. Grain angles of approximately 20° are used.

Table 3: Aging conditions applied to block shear and tapered cantilever specimens.

Identification	Conditions
LH	Conditioned at 85°C and 30% r.h.
HH	Conditioned at 85°C and 85% r.h.
CH	Conditioned at 85°C and 30% r.h. and at 85°C and 85% r.h. on a weekly rotational basis

According to Table 3, LH (high humidity), HH (high humidity) and CH (cyclic humidity) conditions were used to degrade the bond face. For the specimens subjected to cyclic humidity, moisture variation would induce internal stresss. With a degradation mechanism which is purely chemical in nature the strength degradation for the CH specimens could be expected to lie midway between the LH and HH levels. On the other hand, if induced stress levels also played a significant role, then the results would be tend towards the strength loss experienced with the HH specimens. Such tendency is not especially apparent although there is some apparent effect of the induced stresses causing strength loss. The results obtained are shown in Figs 2 (mean strengths) and Fig 3 (5th percentile strengths); similar patterns were obtained with block shear specimens. Unfortunately, the curing ovens malfunctioned during the course of the tests which produces an anomaly in the 28 day exposure results.

Because this combination of adhesive and species exhibits this characteristic it does not follow that all adhesives will exhibit similar behaviour.

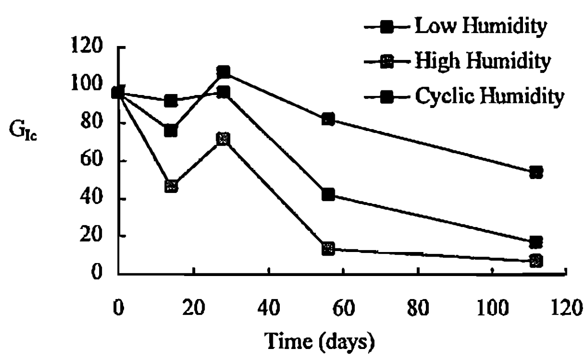

Fig 2 Mean loss of fracture toughness with tapered cantilever specimens. Adhesive: urea formaldehyde, wood species: Mountain Ash. Each data point is based on 10 replicates.

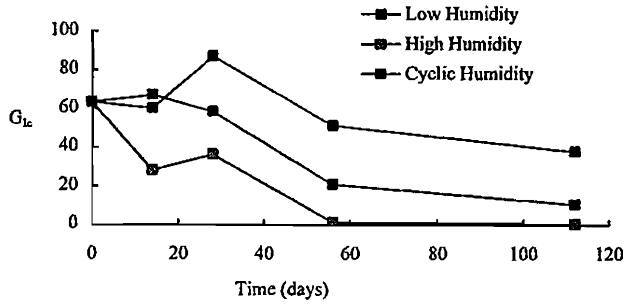

Fig 3 Loss of fracture toughness at 5th percentile level with tapered cantilever specimens. Adhesive: urea formaldehyde, wood species: Mountain Ash. Each data point is based on 10 replicates.

3.2 AITC Approach

For structural glulam, the American Institute of Timber Construction (AITC)[3] have adopted a procedure which is both extensive and expensive. First, a set of simple preliminary screening tests must be passed. The two most dominant are those to ASTM D2559 and ASTM D3434. The ASTM D2559 tests reflect an adhesive's ability to resist shear stress when dry, cleavage during cycles of wetting and drying and creep. ASTM D3434 details a boil test. More extensive durability tests are then carried out on full size glulam members over a three year period in a large environment chamber; see Table 4. Only on satisfactory completion of this test regime is an adhesive deemed acceptable for use.

Table 4: Testing schedule for adhesives used in structural glulam under AITC requirements.

	Initial Grouping		One Year Exposure		Three Year Exposure	
	Test	Control	Test	Control	Test	Control
Original Properties (Base Line)	8	6	—	—	—	—
Test Chamber	16	12	8	6	8	6
Stressed	—	—	4	3	4	3
Unstressed	—	—	4	3	4	3
Outdoor Exposure	16	12	8	6	8	6
Stressed	—	—	4	3	4	3
Unstressed	—	—	4	3	4	3

Under the AITC test regime 70 completed glulam beams are evaluated: 40 beams with the target adhesive and a further 30 beams with a proven PRF adhesive to act as controls. To undertake such tests requires access to large size environment chambers and an outdoor exposure site. The test chamber tests involve conditions of 80% r.h. and 60°C for two weeks followed by ambient conditions for two weeks alternating. The outdoor specimens must be sprayed for between 2 and 4 hours per week during dry periods. At the end of the exposure periods the beams are taken and subjected to testing for MOR and MOE. The stressed beams are loaded at 1.5 times the design bending stress for long term loading. Ultimately, the AITC test method evaluates

[3] American Institute of Timber Construction, Inspection manual AITC 200-83, Annexe E AITC 201-83, AITC 405-86 Standard for Wet-Use Structural Adhesive Types.

adhesive performance under stresses caused by both externally applied load and moisture induced shrink-swell effects. The latter arises with the alternating moisture environment.

The results are evaluated by comparison with with the performance of PRF adhesives exposed to the same test conditions.There are no detailed pass/fail criteria given in Annex E. The AITC simply state that:

Performance of the new adhesive is evaluated by comparison with the performance of PRF adhesives exposed to the same test conditions. Both physical test results and qualitative observations are to be considered.

The AITC test regime appears to be quite rigorous. Early forms of the test regime actually lead to failures of beams with PRF adhesives. The test program is not a cheap one. Some years ago a figure of USD$70,000 was quoted as the cost of testing.

4 GERMAN METHOD

The writer only has in his possession a summary of the German test methods[4]. According to this summary, the testing procedure involves measurement of the following (the list is not complete as it is quite lengthy):

- the adhesive's drying time, wetability and spread characteristics,
- the effect of bond line thickness and climatic conditions on strength - bond line thicknesses of 0.1, 0.5 and 1.0mm are used and the specimens subjected to degradation environments as follows

Temperature °C	RH or Moisture Level	Period
20	65	7 days
20	65 water soak	7 days 4 days
20	65 water soak 65	7 days 4 days to EMC
20 100 20	65 water soak water soak	7 days 6 hours 2 hours
20 100 20	65 water soak water soak	7 days 6 hours 2 hours to equilibrium

- the effect of the production climate on the bonding and aging behaviour-manufacture at 15°C/90% RH, 20°C/65% RH, 30°C/40% RH, measure strength 4h, 8h, 16h, 24h, 48h, 3 days, 7 days, 28 days, 3 months, 6 months, 1 year after manufacture - acceptance criteria vague,

[4] Kemmsies, M, [1996], Introduction of new wood adhesives for glulam timber, Private communication, The Swedish National Testing and Research Institute.

- the effect of alternating climate on the bond strength - half the specimens are tested at 14 days after conditioning at 20°C/65% RH and the remainder subject to a large (144 cycles in one test series) number of cycles of 50°C/100% RH for 24h, 10°C/100% RH for 8h, 50°C/20% RH for 16h,

- the effect of different climates and long term loading on tensile strength (specimens tested at up to 3 years after manufacture) after storage in an open green house (glass roof but with no walls).

5 RECOMMENDATIONS

In developing a test that is compatible with the market size for adhesive bonded products in Australia it is proposed that the following form the basis of rules for adhesive evaluation.

- Preliminary screening be performed in accordance with AITC 201, Annex E. If the adhesive fails these tests then it is automatically rejected as suitable for structural application. In lieu of Douglas Fir and Southern Pine, Radiata Pine and Tasmanian Oak (*e obliqua*) be used as the test species as these dominate the Australian glulam market. This essentially means that the adhesive must pass cold soak, boil and creep tests first.

- The adhesive should be subjected to testing in accordance with ASTM D4502 modified to include both block shear and cleavage. The cleavage specimens are to be prepared in accordance with the principles outlined herein. The block shear and cleavage tests are to involve specimens which are both externally stressed and unstressed and are to cover Radiata Pine and Tasmanian Oak. Test periods and temperatures to cover not only those given in ASTM D 4502, see Table 5, but also the conditions given in Table 6. Control specimens involving a proven PRF adhesive are also to be tested. Detailed acceptance/rejection criteria need to be established for the Service Conditions given in AS/NZS 1491:1996. Satisfactory completion of this test regime would mean that the adhesive could be used in service.

Table 5 Test conditions recommended in ASTM D 4502.

Condition	Temperature °C	Test Period for Durable Adhesive	Test Period for Less Durable Adhesive
Wet	60	146	5.3
	70	50	1.25
	77.5	21.6	0.42
	85	10.8	0.17
	100	2.3	0.10
Dry	120	130	58
	130	55	17
	145	10.3	3.4
	160	2.4	0.85
	170	0.85	0.33

Table 6 Additional test conditions for inclusion in AS/NZS standard. Tests to involve both stressed and unstressed testing of block shear and cleavage specimens.

Condition	Temperature °C	Relative Humidity %	Ageing Period for Adhesives days
High humidity	85	85	0, 7, 14, 28, 56, 112, 224
Cyclic humidity		30 & 85 alternating weekly	0, 7, 14, 28, 56, 112, 224
Low humidity	85	30	0, 7, 14, 28, 56, 112, 224

Relative to the AITC provisions this omits tests on full size glulam members. A program based on the German provisions is recommended as an alternative..

A Shear Strength Assessment of Australian Grown Slash Pine Seasoned at 200° Celsius.

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G.R.Stringer, Hyne and Son, Maryborough, Australia

Abstract

The development of timber seasoning processes over 180°C requires that structural properties of timber products are not adversely affected by such temperatures. This study examines the influence on shear strength of 200°C seasoning of Australian grown plantation Slash pine (Pinus elliottii). Two packs of unseasoned pine were sampled from Hyne and Son's Tuan sawmill and seasoned at 200°C and 140°C. Following grading and machining, test specimens were randomly selected for both small clear and full size shear strength testing. Surface and internal checking, ring width, ring orientation, pith, needle trace and density were recorded. The results of the study indicate that the shear strength of slash pine seasoned at 200°C is not significantly different from slash pine seasoned at 140°C. Density, pith, needle trace and ring orientation all affected shear strength while internal checking, surface checking and ring width had minimal influence. Checking can be greater in 200°C seasoning than in 140°C seasoning. An improved loading configuration for full size shear testing is recommended.

Introduction

Since January 1995, Hyne and Son have been seasoning slash pine at 200°C, having progressively increased drying temperatures from 140°C in 1989. The motivation for the use of such drying temperatures has been to improve product straightness and stability, to reduce drying times and to reduce energy consumption per cubic metre of timber. At a cellular level timber is known to undergo a number of changes in response to temperature increase. (Schaffer 1992) These changes, which may include softening and weight loss of hemicellulose and lignin, can affect the structural properties of the wood. A criteria for the ongoing development of very high temperature drying (VHTD) processes is that structural properties of seasoned timber products should not be adversely affected by the elevated thermal conditions.

The influence of high drying temperatures on structural properties has previously been investigated for slash pine seasoned at 145°C and 200°C. (McNaught and Gough 1995) This study examined the influence of high temperature on the bending strength (MOR), the modulus of elasticity (MOE) and the impact strength. No statistically significant reductions in these properties were found between the two temperatures. Similar results were also found in France. (Martin et al 1984) Both researchers reported slight decreases in checking at the higher temperatures. Martin et al explained this by suggesting the softening at very high temperatures reduced internal stresses and thus checking.

A major evaluation of Australian grown plantation pine (Bolden et al 1994) provided information about the ingrade structural properties of Slash pine. The Hyne and Son samples provided for this study were seasoned at 170°C and the results of the study give some indication of the influence of VHTD. The study showed that the shear strength of slash pine was lower than the shear strength for the total sample population (radiata pine). The shear (5%ile) to bending (5%ile) strength ratio for F5 and F11 stress graded slash pine was 0.19 and 0.18, respectively, while for radiata pine it was 0.30 and 0.20 respectively (Breitinger et al 1994). Hyne and Son seasoned slash pine had strength ratios of 0.20 and 0.16 for F5 and F11 respectively. Are such results due to high temperature degradation of slash pine or are they due to inherent differences between the wood structure of slash pine and radiata pine? These questions, together with concerns about the effect of internal and surface checks on shear strength, have prompted this study the primary objective of which is to quantify the influence of Hyne and Son's current very high temperature drying process on the shear strength of plantation grown slash pine.

Method

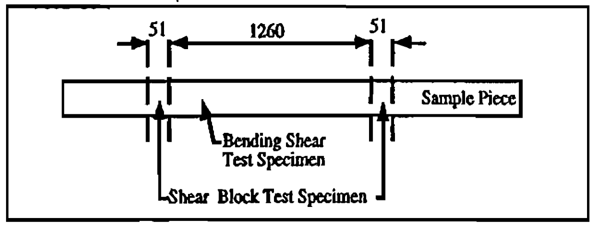
The parameters selected for this investigation were temperature (140°C and 200°C) and stress grade (F5 and F8). Two consecutive produced kiln packs containing 575 pieces of 100 x 40 x 2400 sawn unseasoned slash pine were selected. Consecutive packs produced from similar logs with similar characteristics were chosen to ensure similar basic wood quality and thus minimise the influence of resource variation on the results. The kiln packs were then seasoned in two separate kiln runs. The packs were located in similar positions in the same kiln and one was seasoned in accordance with Hyne and Son's standard 200°C seasoning procedure, while the other was seasoned in a special charge where the only difference was that the maximum temperature was limited to 140°C. Both packs where reconditioned in a similar way in the same reconditioning chamber. A summary of the data from the seasoning process is shown in Table 1.

Table 1. Summary of Seasoning Process.

Target Temperature	140°C	200°C
Maximum Temperature	144°C	203°C
Mean Temperature	134°C	166°C
Drying Time	14h 30min	3h 40min
Time To Target Temp.	50min	2h 5min
Mean MC% Before Reco.	6.6 %	6.6 %
Mean MC% After Reco.	11.2 %	8.8 %

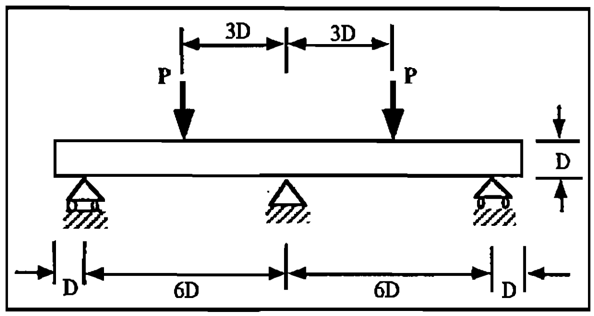
After seasoning, the timber in both packs was machined to a finished size of 90 x 35 and mechanically stress graded. Modulus of elasticity data from the mechanical stress grader was collected for both temperature runs. Prior to packaging, 60 machined and graded samples from each of the two kiln packs were randomly sampled. Each of the 60 samples contained equal quantities of F5 and F8. The two grades were sampled to allow investigation of shear strength differences for different grades and densities groups. Each of the 120 sample pieces were then randomly cut along the length to achieve one bending shear specimen and two block shear test specimens per sample, as shown in Figure 1. Shear block test specimens were cut from the samples so that no discrete wood features were located in the specimen.

Figure 1. Cutting Of Test Specimens



Each of the 120 shear bending test specimens was visually assessed for the occurrence and magnitude of the following features: knots, growth rings, pith, needle trace, surface checks, internal checks and other shear strength influencing features. The density of all specimens was also recorded. The bending shear strength of each specimen was then determined using the five point bending configuration shown in figure 2.

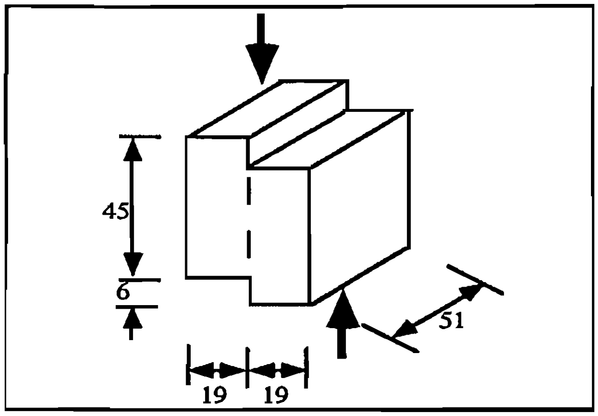
Figure 2. Shear Bending Test Configuration



This test configuration has been described by CSIRO (Brietinger et al 1994), and because of the increased likelihood of shear failures rather than bending failures, is considered to be an improved method to the standard 3 point shear bending configuration given in AS/NZS4063-1992. The objective of this test is to determine the shear strength of the wood that is appropriate to its use as a full size member in a timber structure. The test specimens were randomly orientated in Hyne and Son's Bending Test Machine.

The 240 block shear test specimens were cut to the dimensions defined in AS1328-1987 and shown in Figure 3. The specimens were cut so that the grain was parallel to the direction of loading. Each block shear test specimen was visually assessed in a similar

Figure 3. Block Shear Test Specimen



way to the shear bending test specimens except that the orientation of the growth rings was also recorded. Orientation of the tangent to the growth rings relative to the shear plane in the specimens was measured and assigned to the nearest of the following three values.ie.0°,45°,90°. Knots and other discrete features were not included in the specimens and as a result no data on such features was recorded. The block shear strength test was then undertaken in Hyne and Son's Glulam Plant Laboratory using a special shearing tool described in AS1328-1987. This type of shear test is generally used to evaluate the performance of glued joints and its use in this study is to provide an indication of the effect of 200°C seasoning on clear wood shear strength.

Analysis

The data collected from the specimen measurements and testing was analysed in a number of ways. Firstly statistical comparisons between the mean and fifth percentile shear strengths at both temperatures were carried out. These comparisons were also done on the individual grades investigated. Secondly the influence on shear strength of density, pith, needle trace, growth ring width, surface checks and internal checks was examined. Thirdly the relationship between the two shear strength test methods was investigated by correlating the test results from each method.

Results

The results from the shear bending and shear block tests are summarised in Table 2 and 3 respectively. Table 4 summarises the modulus of elasticity information from the mechanical stress grading. Figure 4 and Figure 5 show the cumulative frequency distributions of the bending shear strength for the 4 different grade and temperature combinations and the two different temperatures, respectively.

Table 2. Shear Bending Test Results

Drying Temperature	140°C			200°C		
Stress Grade	F5 & F8	F5	F8	F5 & F8	F5	F8
Sample Number	60	30	30	60	30	30
Mean Density (kg/m^3)	591 .	563 .	620 .	623 (+5.4)	600 (+6.6)	646 (+4.2)
Standard Deviation	84.6	96.7	59.2	71.5	68.2	68.4
Surface Checks (no.)	27 .	8 .	19 .	43 (+59)	17 (+110)	26 (+37)
Internal Checks (no.)	11 .	4 .	7 .	40 (+260)	18 (+350)	22 (+210)
Surface & Internal (no.)	32 .	10 .	22 .	54 (+69)	26 (+160)	28 (+27)
Shear Strength (MPa)						
Mean	8.6 .	8.3 .	9.1 .	8.6 (0)	7.7 (-6.7)	9.7 (+6.6)
Standard Deviation	1.7	1.7	1.6	1.8	1.7	1.3
Fifth percentile	6.0 .	5.2 .	6.8 .	5.7 (-5)	5.2 (0)	6.9 (+1.5)

Note: The numbers in brackets indicate the percentage difference between the 140°C and 200°C.

Table 3. Shear Block Test Results

Drying Temperature	140°C			200°C		
Stress Grade	F5 & F8	F5	F8	F5 & F8	F5	F8
Sample Number	120	60	60	120	60	60
Mean Density (kg/m^3)	567 .	551 .	582 .	593 (+4.4)	559 (+1.3)	627 (+7.3)
Standard Deviation	64.6	67.4	58.8	67.6	57.9	59.5
Shear Strength (MPa)						
Mean	8.3 .	7.9 .	8.8 .	8.7 (+4.7)	7.9 (+0.9)	9.5 (+7.7)
Standard Deviation	1.8	1.5	1.9	1.6	1.5	1.4
Fifth percentile	5.2 .	5.5 .	5.4 .	5.5 (+5.4)	5.2 (-5.8)	6.8 (+20.6)

Note: The numbers in brackets indicate the percentage difference between the 140°C and 200°C.

Table 5 shows the effect of ring orientation on block shear strength, while the effect of pith and needle trace on the mean bending shear strength is shown in Table 6. The effect of checking is shown in Table 7. The relationship between the density of the shear test blocks and the shear strength is shown in

Table 4. Mechanical Stress Grading Data

Drying Temperature	140°C		200°C	
Stress Grade	F5	F8	F5	F8
Number	228	236	167	217
Mean MOE(MPa) % diff.	10470 .	13850 .	10270 -1.9	14660 +5.8
Mean Low MOE(MPa) % diff.	6330 .	9040 .	6290 -0.6	9430 +4.3

Figure 4. Cumulative Frequency Distribution of Bending Shear Strength for F5, F8, 140°C and 200°C.

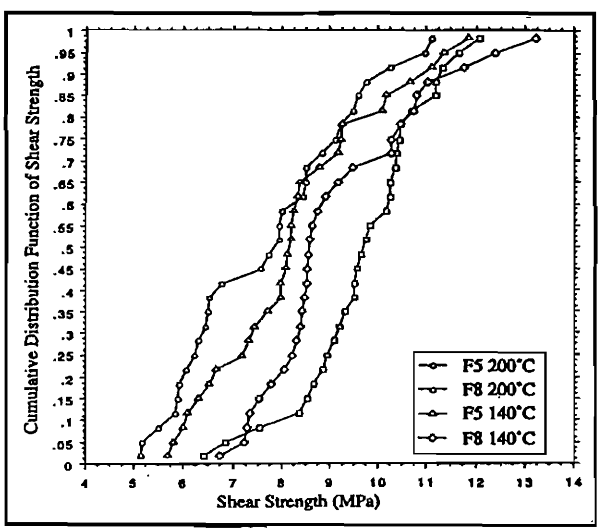


Figure 5. Cumulative Frequency Distribution of Bending Shear Strength for 140°C and 200°C.

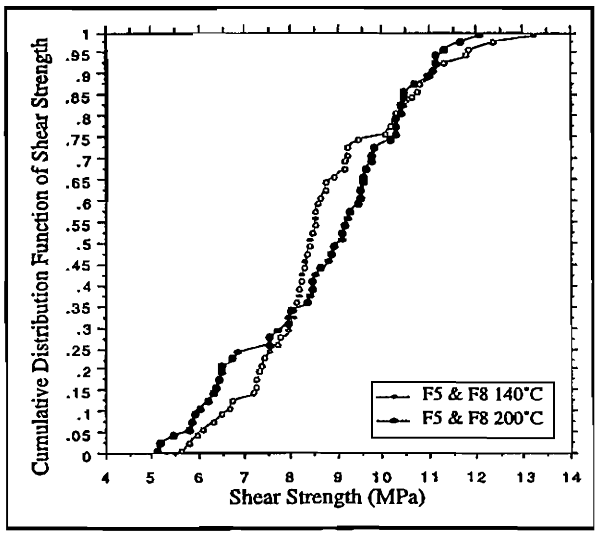


Table 5. Effect of Ring Orientation

Orientation (degs)	0°	45°	90°	ALL
Number	45	177	18	240
Mean Block Shear Strength (MPa)	8.77	8.63	6.69	8.51
Std. Dev. (MPa)	1.93	2.15	1.85	2.15

Table 6. Effect of Pith and Needle Trace

Sub-Population	No.	Mean Bending Shear Strength (MPa)	Std Dev (MPa)
Pith-in only	37	7.72	1.64
No Pith-in	83	9.12	1.62
Needle Trace only	79	8.20	1.76
No Needle Trace	41	9.62	1.27
Total	120	8.69	1.74

Figure 6. Block Density (kg/m^3) Vs. Block Shear Strength (MPa).

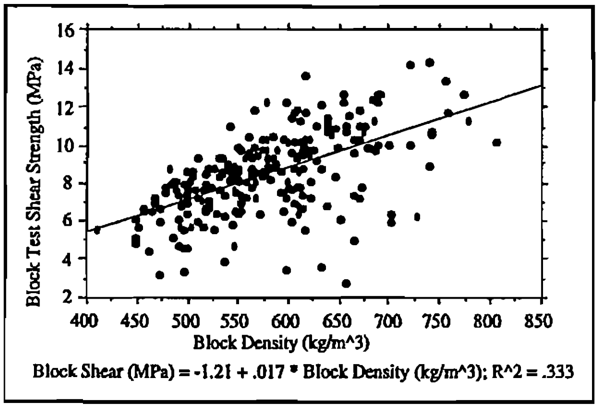


Figure 6. The relationship between the width of growth rings and the shear strength from both the bending and block tests is shown in the following two equations which are not statistically significant.

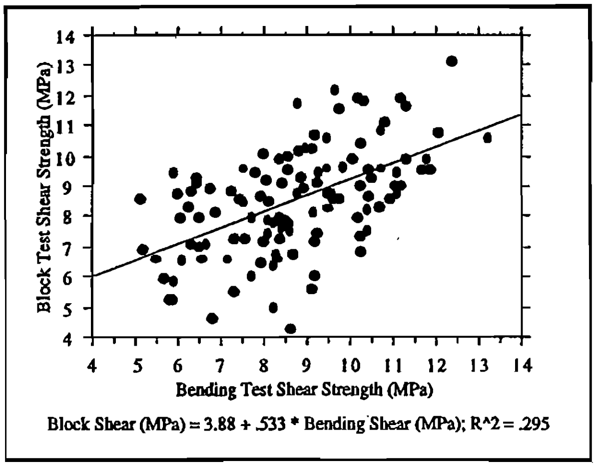
Bend. Shear(MPa) = 10.06 - 0.16 x Ring Width(mm)
R^2=0.087 N=120

Block Shear(MPa) = 9.84 - 0.17 x Ring Width(mm)
R^2=0.059 N=240

The relationship between the small clear and full size shear strength values determined from the two different test methods is shown in Figure 7.

The statistical significance between the mean density, mean shear strength and 5 percentile shear strengths of the 140°C and 200°C populations was determined. The difference between the densities was not significant for the F8 bending shear samples or the F5 block shear samples. All other density differences were statistically significant. All five percentile strength differences were not significant, except for the F8 block shear strengths where the 200°C samples were 20% higher. The only significant difference in mean shear strength that was less for 200°C was the F5 bending shear which was 6.7% below the 140°C value. The differences in proportions of sample populations with surface and internal checks was statistically significant between 140°C and 200°C.

Figure 7. Block Shear Strength (MPa) Vs Bending Shear Strength (MPa).



Discussion

Despite the effort put into both the sampling and the maintenance of similar processes for the two sample packs, differences in the density and moisture content of the finished product occurred. A model relating low moisture content to the average small clear strength of Southern Pine (either P. echinata or P. taeda) has been developed. (Kretschmann and Green 1994). The application of this model to the 2.4% moisture content difference between the two specimen groups suggests that the wood with a lower moisture content will have a parallel-to-grain shear strength which is greater by 5.4%. This

Table 7. Effect Of Surface and Internal Checking

Drying Temperature	140°C				200°C				140°C 200°C
Internal Checking	YES	NO	-	-	YES	NO	-	-	Total
Surface Checking	-	-	YES	NO	-	-	YES	NO	Sample
Bending Shear Test Number	11	49	27	33	41	19	44	16	120
Mean Shear Strength (MPa)	8.42	8.76	9.04	8.41	8.53	9.01	9.12	7.49	8.69
Block Shear Test Number	1	119	8	112	45	75	24	96	240
Mean Shear Strength (MPa)	8.84	8.30	9.33	8.24	8.28	8.98	9.52	8.51	8.51

may in part explain the slight strength increase found in the shear block test results for the 200°C specimens. The influence of moisture content on full size timber has not been as well established, although Madsen (1992) has suggested that below a moisture content of 15%, full size shear strength may reduce, particularly the five percentile strength.

The increase in checking at the higher temperature is inconsistent with other studies (McNaught & Gough 1992; CTBA 1985; Martin et al, 1984). Hyne and Son staff also report that this increase in checking is not typical for 200°C dried softwood. They suggest that the relatively slow heat up to the 200°C target temperature has caused the increase in checking seen in this study.

The difference between the shear strengths of the two temperatures is quite negligible. The statistical difference analysis showed that the majority of the decreases from 140°C to 200°C were non significant, while some of the increases were significant. In general, it appears that the difference in seasoning temperatures does not adversely affect the shear strength of F5. While for F8, the results seem to show an increase in shear strength in the 200°C material. This is however, probably due to the density and moisture content differences between the samples.

It is of some interest to compare these results with the full size (90x35) shear strength results found in other studies. Table 8 summarises the results of this study and the CSIRO study. Making such comparisons is difficult as the particular grading methods used in each study may vary between mills and over time. Nonetheless it is clear from these results that the shear strength of Hyne and Son produced F5 and F8 slash pine, seasoned at 200°C is similar to previous Hyne and Son production and to the shear strength of F5 and F8 radiata pine.

The influence of internal and surface checks on the shear strength shown in Table 7 is quite negligible. Internal checks appear to have a slightly negative effect on shear strength. It is interesting to note that the mean shear strength of pieces containing surface checks is higher than pieces with no surface checks. This is likely to be due to the tendency of higher density backsawn pieces to exhibit surface checking. The higher density wood is known to be stronger and obviously has a greater effect on shear strength than do surface checks.

Table 6 shows the more significant influence of pith or needle trace on mean shear strength. This influence is supported by observations of the failed specimens, where planes of failure corresponding with the earlywood/latewood boundaries at the end of needle trace were common. Slash pine has a more pronounced density difference between earlywood and latewood than does radiata pine and it may be the shear strength at this interface which causes the species difference reported by Brietinger et al (1994). Ring orientation in the shear block tests has also had some influence on shear strength with rings at 90° to the shear plane showing the greatest reduction in shear strength. A 90° orientation corresponds to beam shear in backsawn sections and perhaps reflects the inherent shear strength of the rays or the effect of minute fibre separation along the rays, ie. internal checking.

Table 8. Comparison of 90 x 35 Shear Strength Results

Source of Information	Stress Grade (Temperature)	Number of Tests	Mean Shear Strength (MPa)	C.O.V.	5%ile Shear Strength (MPa)
CSIRO-DBCE 1993	F5	36	8.2	0.22	4.5
Hyne & Son Mill Only	F11	40	11.4	0.12	8.3
CSIRO-DBCE 1993	F5	79	7.9	0.16	4.9
Pine Australia	F8	79	9.2	0.14	6.2
Radiata Mills Only	F11	79	11.0	0.15	7.6
This study	F5 (140°C)	30	8.3	0.20	5.2
	F8 (140°C)	30	9.1	0.18	6.8
	F5 (200°C)	30	7.7	0.22	5.2
	F8 (200°C)	30	9.7	0.13	6.9

The comparison between the small clear shear strengths and the full size shear strengths shows that the block shear test is generally more likely to give conservative estimates of full size bending shear strengths. Knots in timber may actually result in an increase in shear strength, due to the disturbance in grain around the knot and the resulting interruptions to the likely failure plane.

Conclusions

1. The shear strength of slash pine seasoned at 200°C is not significantly different from slash pine seasoned at 140°C.

2. Shear strength in slash pine is influenced by density, pith, needle trace and ring orientation.

3. Internal checking, surface checking and ring width have a minimal influence on shear strength.

4. Shear block tests using small clear specimens provide a conservative estimate of the shear strength of full size timber members.

5. Seasoning timber at 200°C can result in significantly more checking than timber seasoned at 140°C.

6. The inherent shear strength of slash pine seems to be related to the strength of the bond between latewood and earlywood.

Recommendations

1. The further development of very high temperature drying at Hyne and Son can continue with the confidence that shear strength is not adversely influenced by seasoning temperatures at 200°C.

2. A slight modification to the load configuration of the full size shear test proposed by CSIRO should be considered. A summary of the current full size shear test configurations is shown in Figure 8 together with moments, shears and the ratios of moment to shear. The proposed configuration has the advantage of having a constant shear force along the length of the specimen without adversely increasing the moment/shear ratio. As shear failures are generally quite longitudinal in nature, maintenance of a constant shear force will allow a more accurate shear strength to be determined. The CSIRO method induces different shear stresses along the member and upon failure the particular region of the member causing failure cannot always be determined. CSIRO appear to assume that the higher central stress always causes the failure, when in fact shear defects near ends subject to lower shear stresses may initiate the failure. A uniform shear stress along the member would eliminate this problem and allow improved estimates of shear strength without greatly compromising the achievement of shear failures in lieu of bending failures.

Figure 8. Summary of Shear Bending Test Load Configurations.

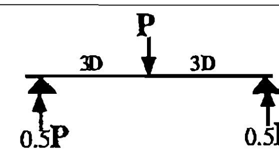
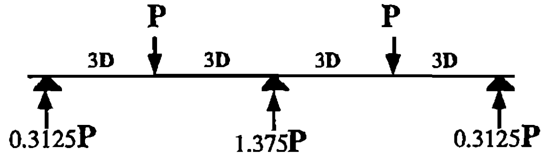
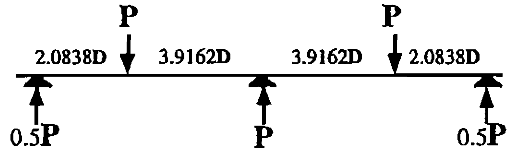
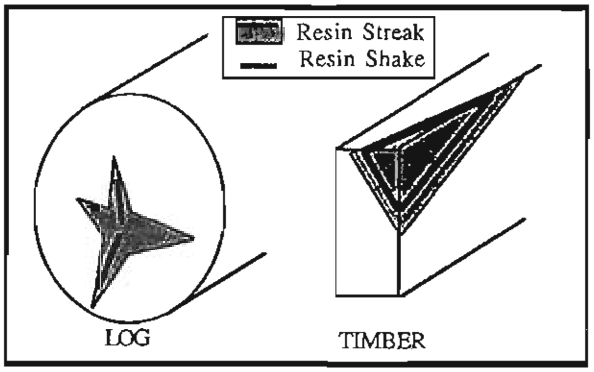
TEST METHOD	TEST CONFIGURATION	MOMENT	SHEAR	RATIO
Standard Shear Bending Test AS/NZS4063		0.25PL	0.5P	0.5L
CSIRO Shear Test (Brietinger et al 1994)		0.1875PL 0.1563PL 0.1563PL	0.6875P 0.6875P 0.3125P	0.273L 0.227L 0.5L
Proposed Modification to CSIRO Shear Test		0.1527PL 0.1737PL	0.5P 0.5P	0.3054L 0.3473L

Figure 1. Resin Shakes in logs and timber.



Two independent internal Hyne and Son studies (Stringer 1994, Lavielle et al 1995), have shown that resin shakes account for about 25% of timber pieces considered as unsuitable for Hyne and Son structural framing. Resin shakes are the main reason for down grading slash pine and individually exceed other reasons, such as knots, distortion and wane. Although Hyne and Son use a mechanical stress grading (MSG) machine to assign a stress-grade to their timber, features affecting shear strength still need to be assessed using visual grading techniques. (Standards Australia 1978) Prior to the study reported herein the conservative visual grading rule adopted by Hyne and Son, based on customer feedback was that, resin shakes, of any size, are not permitted in structural softwood.(Hyne and Son 1994) This is considerably more restrictive than the minimum requirement suggested in AS2858 "Timber- softwood-visually stress-graded for structural purposes" (Standards Australia 1986). Resin shakes are not specifically defined in this standard and the feature considered to be most similar to resin shakes is heart shakes. In structural grades 4 and 5 "heart shakes" up to 3mm in width and not extending from one surface to another are permitted.

As resin shakes significantly affect Hyne and Son's recovery of structural products, an investigation of resin shake features and their influence on shear strength was considered necessary. The criteria adopted for developing any new visual grading rule was that it should result in equivalent or better shear strength performance than the current AS2858 rule. The perceived benefits to Hyne & Son of this evaluation are increased confidence in the shear strength of their structural softwood products and improved grading efficiencies.

Method

The strategy used in this study was to test pieces of rejected softwood framing which contained resin shakes. The sampling strategy aimed to ensure that the test population had a wide variation of resin shake features. By measuring the varying features and then evaluating the shear strength of the pieces, the relationship between each could be established and potential grading rules developed. This data set of test information could then be used to assess a number of visual grading rule options.

Sampling

A total of 123 pieces of 90 x 35 rejected slash pine framing were sampled. All pieces contained resin shakes. Each sample was produced using Hyne and Son's standard production practices, including seasoning at 200°C and mechanically stress grading to AS1748. (Standards Australia 1978) In most samples a stress grade was assigned by the MSG machine, however this was overridden by Hyne visual grading rules.(Hyne and Son 1996) A test specimen, 1260 mm in length, was selected from each sample such that the resin shake was located centrally in the specimen. Each sample, specimen and resin shake feature therein was then examined and the following information was recorded.

- **-stress grade;** <F4, F4, F5, F8 or F11. (Grade is also a good indicator of wood density in slash pine.)
- **-resin shake features;** shake length, resin width, shake width, orientation relative to the arris.
- **-resin shake location**; on an edge, on a face, one face to another, in the margin or central portion of the section.
- **-other wood features;** knots, over growth of injury, pith, needle trace, growth ring width.

Figure 2 defines the terms arris, central portion, margin, edge and face.

A visual classification system indicating the occurrence of resin shakes on one or more faces or edges was devised and used in the study. This system is defined in Table 1.

Figure 2.Terminology used in evaluation.

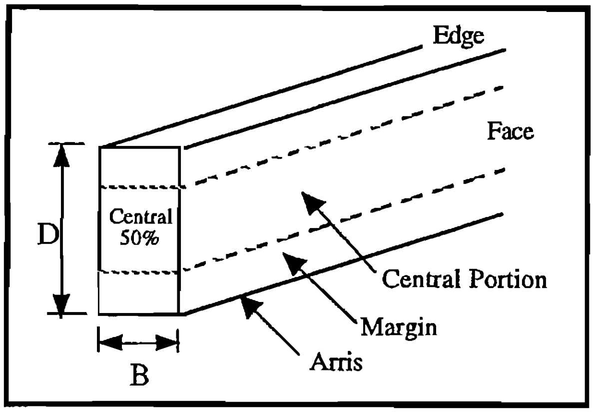


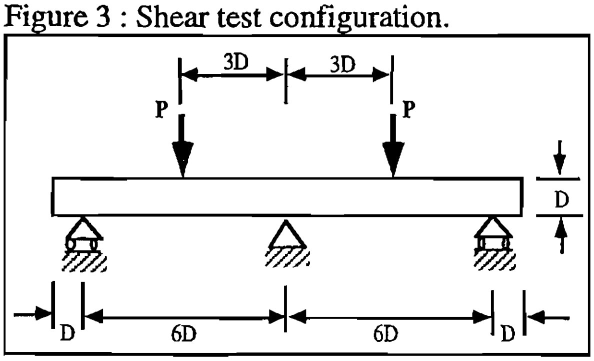
Table 1. Classification of resin shakes.

Code	Description
RS1	Occurs on one edge only
RS2	Occurs on one face only
RS3	Occurs on both edges only
RS4	Occurs on both faces only
RS5	Occurs on an adjacent face and edge
RS6	Occurs on three surfaces
RS7	Occurs on all four surfaces

Strength testing

Shear strength testing was carried out in accordance with the requirements of AS 4063 (Standards Australia 1992) except that the loading configuration was amended to a double span, based on a recent analysis of shear test configurations. (Brietinger 1994) Shear strength is not the usual structural property controlling the design of timber members in structures, however the test method adopted simulates a loading configuration where the mode of failure is likely to be initiated by the inherent shear strength of the timber or any feature therein which has a low shear strength. A diagram of the test configuration is shown in figure 3.

Figure 3 : Shear test configuration.



For each test specimen the maximum load was recorded and the shear strength at failure was determined. The mode of failure was established and the most likely reason for initiation of the failure was noted.ie. bending (knots), shear (resin shake, growth ring or pith), or a combination of both.

Analysis

The aim of the analysis was to establish the relationship between different resin shakes features and shear strength.

Initially the specific features of the resin shakes were characterised. The influence of these features on shear strength was then evaluated and the features with greatest influence were used to develop a number of potential visual grading rules for assessment. A total of 21 rules were developed and these were assessed by comparing the effects on recovery, mean shear strength and fifth percentile shear strength. The significance of the differences with the AS2858 rule were also investigated.

Results

The proportion of resin shakes in the sampled population, using the system described in table 1 is shown in table 2.

Table 2. Proportion of Resin Shakes.

Resin Shake Code	Percentage %
RS1	2
RS2	37
RS3	1
RS4	9
RS5	27
RS6	19
RS7	5

The stress grades assigned to the sample population by the MSG machine is shown in table 3.

Table 3. Stress Grade of Samples

Stress Grade	Percentage %
Less than F4	11
F4	7
F5	49
F8	23
F11	10

The mean length of resin shakes, width of the resin streaks, width of resin shakes and width of growth rings associated with shakes for the 123 test specimens is shown in table 4.

Table 4. Mean characteristics of resin shakes.

Characteristic	Mean Value
Resin Shake Length	610 mm
Resin Shake Width	1.4 mm
Resin Streak Width	11.0 mm
Growth Ring Width	8.5 mm

A comparison between the mean and 5 percentile shear strengths of the F5 and F8 resin shake samples and the known (Lavielle & Gibier 1995) shear strengths of Hyne F5 and F8 with no resin shakes is shown in Table 5.

Table 5 : Shear strength comparisons.

Population Details	Stress Grade	
	F5	F8
No Resin Shake (Lavielle et al 1995)		
- sample no.	30	30
- Mean (MPa)	7.7	9.7
- 5%ile (MPa)	5.2	6.9
All Resin Shakes (This study)		
- sample no.	61	28
- Mean (MPa)	7.3	7.2
- 5%ile (MPa)	4.4	4.9

The failure of each sample was closely observed and Table 6 summarises the modes of failure and the main wood features contributing to that failure.

In table 6 "Ring" indicates a failure along the growth ring particularly at the latewood - earlywood boundary.

It can be seen from table 6 that resin shakes where associated with about 73% of the shear failures while ring failure and pith failure were associated with 52% and 39% respectively.

The expression for the influence of ring width on shear strength was found to be,

Shear Strength (MPa) = 8.9 - 0.19 x Ring Width (mm).; $R^2 = 0.20$

Table 6. Failure modes and wood features contributing to failures

Failure Mode		Reason for Failure	
Type	%	Wood Features	%
Shear	83	Resin Shake (RS) only	15
		Ring only	17
		Pith only	1
		Resin only	1
		RS & Pith	15
		RS & Ring	13
		RS & Knot	4
		Pith & Ring	2
		RS & Pith & Ring	11
		RS & Pith & Knot	3
Bending	8	Knots	8
None	9	Buckling occurred at high loadings and testing was stopped for safety reasons	9

The influence of resin width and resin shake length on the shear strength were both found to be negligible. The influence of shake width on shear strength was more significant and is given by the following expression.

Shear Strength (MPa) = 7.6 - 0.29 x Shake Width (mm).; $R^2 = 0.13$

The influence of pith on shear strength is shown in Table 7.

Table 7. Influence of pith on shear strength

Population Details	Presence of Pith	
	Pith	No Pith
- sample no.	51	72
- Mean (MPa)	6.3	7.9
- 5%ile (MPa)	3.4	5.1

The influence of needle trace on shear strength was analysed and is summarised in Table 8.

Table 8. Influence of needle trace on shear strength.

Population Details	Presence of Needle Trace	
	Needle Trace	No Needle Trace
- sample no.	95	28
- Mean (MPa)	6.8	8.6
- 5%ile (MPa)	4.1	6.0

The influence on shear strength of the type of resin shake in the test specimens is summarised in Table 9.

Table 9. Influence of resin shake type.

Resin Shake Code	Number	Mean Shear Strength (MPa)
RS1	2	8.0
RS2	46	7.6
RS4	11	6.7
RS5	33	7.4
RS6	25	6.7
RS7	6	5.9

The influence on shear strength of the orientation of the resin shake to the arris was analysed and a predictable but relatively weak relationship was identified. ie.

Shear Strength (MPa) = 8.0 - 0.84 x Shake Orientation (degrees).

The influence on shear strength of the location of the shake within the section was determined and is summarised in Table 10.

Table 10. Influence of resin shake location

Population Details	Location of Resin Shake	
	Centre	Margin
- sample no.	70	53
- Mean (MPa)	7.1	7.4
- 5%ile (MPa)	4.1	5.0

Based on the above analysis, observation of failures and some theoretical considerations the features of slash pine which influence shear strength where classified in order of relative importance. See Table 11.

Table 11. Importance of Natural Features

Natural Feature Influencing Shear Strength	Relative Importance
	Critical - 10 Irrelevant - 1
pith	9
shake width	8
type of resin shake	8
needle wood	7
ring	6
resin shake location	5
resin shake orientation	5
knots	4
resin shake length	3

This classification was then used to develop a number of potential visual grading rules for resin shakes in slash pine. The current rule given in AS2858 was also defined using the resin type classification given in Table 2. A list of the potential rules which were investigated are given in Table 12.

Using the population of 123 pieces containing resin shake the potential grading rules were applied and the mean and five percentile shear strengths were calculated. The significance of any difference from the AS2858 mean shear strength was also determined. This analysis is shown in Table 13.

Discussion

The presence of resin shakes in slash pine structural framing can have a negative influence on shear strength. Table 5 suggests the magnitude of this reduction in shear strength could be about a 5% to 15% in F5 and about 25% to 30% in F8 products. Assuming the bias sample (ie.100% of pieces contain resin shake) used in this study provides a worst case estimate of the influence of resin shake on shear strength, the real reduction in shear strength of a population which included run-of-mill resin shake (about 5% of pieces contain resin shake) is likely to be quite negligible.

The results highlight the negative influence of pith, needle trace and ring width on shear strength. Another study at Hyne and Son (Lavielle et al 1995) has shown similar reductions in mean shear strengths due to the presence of pith or needle trace. In this study the negative influence of pith and needle trace appears to be due to a weak bond between timber fibres at the latewood - earlywood boundary, particularly near the centre portion of the tree. Observations of failures showed a high incidence of shelling type wood separation associated with this region. In particular failure at the boundary where needle trace finishes was very common. As visual grading rules necessarily focus on macro wood features it is not possible to assess by eye the relative strength of this earlywood - latewood boundary, although by using associated features in grading rules, like pith, needle trace and growth ring width its influence on shear strength can be considered.

The influence of shake width and type of

Table 12. Potential rules for resin shake.

Rule No.	Description of Rule
Hyne Rule	No Resin Shake
AS2858	Shake Width < 3mm, No RS3-RS7
1	No Pith
2	Shake Width < 2mm
3	Shake Width < 1mm
4	No RS7
5	No RS7, No RS4
6	No RS7, No RS4, No RS6
7	No Pith, No Needle Trace
8	No Pith, Shake Width < 2mm
9	No Pith, Shake Width < 1mm
10	No Pith, Shake Width < 1mm, No RS7
11	No Pith, Shake Width < 1mm, No RS7, No RS4
12	No Pith, Shake Width < 2mm, No Needle Trace
13	No Pith,Shake Width < 1mm, No Needle Trace
14	No Pith,Shake Width < 1mm, No RS7, No Needle Trace
15	No Pith,Shake Width < 1mm, No RS7, No RS4, No Needle Trace
16	No Pith, No RS7, No RS4
17	No Pith, No RS7, No RS4, No Needle Trace
18	No Pith, Shake Width < 2mm, No RS7, No RS4, No Needle Trace
19	No Pith, Shake Width < 2mm, No RS7, No Needle Trace
20	No Pith, Shake Width < 2mm, No RS7
21	No Pith, Shake Width < 2mm, No RS7, No RS4

shake are somewhat predictable from a strength of materials and structural mechanics viewpoint, respectively. Wider shakes are likely to have less bonding and therefore are less likely to resist shear stresses. The occurrence of resin shakes on two faces particular near the centroidal axis corresponds with the zone of maximum shear stress in a member subjected to bending.

The main criteria for a commercial acceptable grading rule are strength, grade recovery, appearance, safety and utility.

The resulting strengths and grade recoveries for each rule is shown in Table 13. The application of the proposed rules to this biased sample population is somewhat inappropriate as the occurrence of resin shakes in every piece in a standard population of slash pine framing would be quite atypical. A more detailed and technically correct evaluation of the shear strength on an unbiased population would require about 100 samples per combination of rule and grade. (about 8000 pieces) Such an extensive study is not justifiable however, the application of the potential rules to the biased population used herein is expected to provide relative lower bound information which will allow the effect of different rules on shear strength to be adequately assessed.

After considerable discussion with Hyne and Son's production staff about the merits of each rule, including its simplicity and ease of application, it was decided that rule 8 (a combination of rule 1 and rule 2) was the most appropriate. This rule provides a shear strength in the sample population which is about 10% greater than the shear strength resulting from the AS2858 rule. It also allows about 50% of pieces currently being rejected to be recovered into structural products.

Acceptable appearance, safety and utility issues associated with resin shakes have been defined by Hyne and Son. ie.

Appearance:- Individual shakes to be less than 600 mm

Safety:- Shakes causing splintering on the arris are not permitted.

Utility:- Resin shakes within 150 mm of ends are not permitted.

Table 13. Analysis of Grading Rules.

Rule	Compliance		Shear Strength (MPa)		AS2858	Grade Recovery (No.)			
	No.	%	Mean	5%ile	Comparison	F8+	F5	F4	< F4
Hyne Rule	0	0	-	-	-	-	-	-	123
No Rule	123	100	7.21	4.25	ns	41	60	9	13
AS2858	48	39	7.64	5.08	-	17	20	3	8
Rule 1	72	59	7.86	5.15	ns	31	34	1	6
Rule 2	90	73	7.68	5.02	ns	33	40	8	9
Rule 3	75	61	7.70	5.57	ns	26	35	7	7
Rule 4	117	95	7.27	4.42	ns	39	58	8	12
Rule 5	106	86	7.33	4.98	ns	35	53	8	10
Rule 6	81	66	7.53	5.50	ns	30	25	7	9
Rule 7	28	23	8.58	6.00	ns	14	12	1	1
Rule 8	58	47	8.26	5.75	0.01	26	27	1	4
Rule 9	49	40	8.33	5.80	0.05	22	23	1	3
Rule 10	48	39	8.31	5.79	0.05	21	23	1	3
Rule 11	44	36	8.37	5.77	0.05	18	22	1	3
Rule 12	25	20	8.84	6.25	0.05	13	10	1	1
Rule 13	23	19	7.78	6.10	0.01	11	10	1	1
Rule 14	22	18	8.76	6.05	0.01	10	10	1	1
Rule 15	20	16	8.87	6.20	0.01	9	9	1	1
Rule 16	63	51	7.99	5.77	0.01	26	31	1	5
Rule 17	25	20	8.62	5.85	ns	12	11	1	1
Rule 18	22	18	8.93	6.39	0.01	11	9	1	1
Rule 19	24	20	8.83	6.20	0.001	12	10	1	1
Rule 20	57	46	8.25	5.72	0.01	25	27	1	4
Rule 21	53	43	8.29	5.71	0.05	22	26	1	4

Note: The letters "ns" indicate not significant, while "0.05","0.01" and "0.001" indicate the level of significance.

Despite the development of the above grading rule for resin shakes, its application to commercial grading processes are somewhat stifled by the prescriptive nature of AS2858. Compliance to this standard is required under building legislation in Australia and also by state based timber marketing legislation like the NSW Timber Marketing Act. This standard fails to set performance requirements for structural softwood products and does not provide a means of endorsing alternative grading rules.

Conclusions

1. Resin shakes in sawn Slash pine timber can reduce shear strength

2. The features of resin shakes which most influence shear strength are,
 i) needle trace associated with the shake,
 ii) pith associated with the shake,
 iii) the width of the shake, and
 iv) the occurrence of the shake on two faces.

3. The features of resin shakes which least influence shear strength are,
 i) the length of the shake,
 ii) the orientation of the shake to the arris,
 iii) any knots associated with the shake.

4. The AS2858 "Heart Shake" rule when applied to resin shakes is effective at increasing shear strength.

5. Alternative visual grading rules for resin shakes can give improved shear strengths relative to the AS2858 rule, without adversely reducing the amount of structural timber recovered.

6. AS2858 is stifling of grading innovations as it does not define the performance of graded timber or provide a means of endorsing grading innovations.

Recommendations

1. It is recommended that the following grading rule for resin shakes be adopted, at Hyne and Son's Tuan Sawmill.

Strength:	Resin shakes shall not be in combination with pith and shall not be greater than 2mm in width
Appearance:	Individual resin shakes shall be less than 600 mm
Safety:	Resin shakes causing splintering on the arris are not permitted.
Utility:	Resin shakes within 150 mm of ends are not permitted.

2. It is recommended that the shear strength of the latewood-earlywood boundary and its relationship with the density of each wood be studied.

3. The Standards Australia committee responsible for AS2858 should amend this document to,

i) specifically include resin shakes,
ii) define the performance requirements of visually graded timber,
iii) provide a means by which grading innovations can be endorsed.

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AN ASSESSMENT OF FACTORS INFLUENCING DISTORTION IN SLASH PINE FRAMING

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ABSTRACT

Marketplace demands for straighter and more stable pine framing require that processors have an understanding of the fundamental wood features that cause distortion. An investigation of the relationships between distortion (spring, bow and twist) and a number of wood features, in 70 x 35 and 90 x 35 Slash pine framing, was undertaken. The sampled timber was stored in strapped packs for 23 weeks, after which it was stored in a fully unrestrained condition for an additional 12 weeks. Distortion measurements were taken at 1, 10, 23 and 35 weeks. The main factors influencing initial straightness were found to be moisture content, growth ring width and the proximity of the section to the pith. The main influence on stability was the initial moisture content of the timber. Processors can produce straighter and more stable framing by minimising juvenile wood in framing and minimising variation in moisture content, respectively. Avoiding juvenile wood in framing products is not practical.Softwood growers should assist producers by minimising the variation in wood characteristics between juvenile and mature wood. An explanation of distortion based on variation in longitudinal stain within sawn sections is provided.

INTRODUCTION

In recent years the increased promotion of steel framing as a perfectly straight and stable product has resulted in timber users demanding increasingly straight and stable timber framing products. This is a significant challenge for timber producers as these market demands for straighter products comes at the same time as many timber producers are being forced to process younger trees with increasing amounts of juvenile wood.

A number of strategies are available for improving the straightness and stability of softwood products. eg.finger jointing, improved seasoning, improved sawing practices. At Hyne and Son a number of strategies have been adopted. The one reported herein is the assessment of the relationships between distortion and wood quality in Slash Pine (Pinus elliotii), the aim of which is to obtain a better understanding of the factors influencing distortion, so that improvement in sawing or seasoning processes can be pursued. This paper summarises some of the information contained in the full project report. (Stringer 1994)

MATERIALS AND METHODS

Preliminary investigations of distorted framing both within sawmills and on domestic construction sites were carried out. This revealed considerable anecdotal information about the wood quality features which most influence distortion. In particular, the presence of pith in a piece was perceived as the main influence on straightness and stability. It was decided to select typically produced pine framing and measure its distortion at three intervals over at least 6 months. The timber was to be initially stored in strapped packs and towards the end of the period be placed in unrestrained storage, to simulate loose raked storage, similar to open racking in timber merchants yards.

CONCLUSIONS

1. The initial straightness of Hyne pine framing products will increase as,

- initial moisture content decreases
- growth ring width increases
- the distance from the pith decreases

2. The stability of the Hyne pine framing will improve where the initial moisture content is kept to a minimum.

RECOMMENDATIONS

1. Producers of softwood framing products who wish to minimise initial and long term distortion in their products, should focus their processing efforts on sawing and seasoning respectively. In particular, sawing to avoid distortion prone juvenile wood and seasoning to achieve moisture content distributions with minimum variation.

2. Softwood forest managers, who wish to improve the suitability of their trees for processing into sawn products, should focus their breeding and silvicultural efforts on reducing the variation between juvenile wood and mature wood. In particular, variations in growth ring width, spiral grain, microfibral angle and responsiveness to moisture content changes.

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OUTPUT CONTROL OF MECHANICALLY STRESS GRADED SLASH PINE. A CASE STUDY

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ABSTRACT

A European developed method for controlling timber grading systems has been implemented in Hyne and Son's softwood sawmill at Tuan. This method, which includes a CUSUM statistical procedure, is referred to as "output control". It involves the daily sampling of product and the evaluation of primary structural properties.ie. Bending strength and stiffness. After seven months of using output control, all structural test information was collected and analysed in accordance with AS/NZS 4063 and AS/NZS YYYY. Relationships between design values and machine settings were established as were MOE versus graded length relationships. The adoption of output control procedures in sawmills provides a range of benefits, including;

i) Better control of structural properties and grading processes
ii) Evidence of structural property compliance on a daily basis
iii) Improvements in timber grading systems
iv) Increasingly efficient resource processing and utilisation
v) Increased designer confidence in the structural properties of timber products.

All producers of structural timber should consider implementing output control systems.

INTRODUCTION

The implementation of the results from the major Pine Australia-CSIRO study on the structural properties of Australian grown plantation softwood (Bolden et al 1994) has seen in the introduction of three new grades of structural softwood. ie. MGP10, MGP12 and MGP15. The properties of these grades exceed those of the corresponding "F" grades and as such Pine Australia softwood timber producers are now making increased claims about these products. Corresponding to the introduction of "MGP" grades has been a total review and upgrading of the processes associated with structural softwood production. Many new initiatives that assist producers to achieve a more reliable product have been developed by Pine Australia in conjunction with CSIRO. These improved procedures are defined in the Pine Australia Quality Control Manual, (Pine Australia 1995) and include improvements in mechanical stress grader operation, initial property establishment, process control procedures and output control procedures. Output control is a method of controlling a timber grading system through the daily testing of specimens drawn from the output of the grading process. The use of a CUSUM statistical procedure to analyse the daily test results provides immediate feedback regarding the integrity of the grading process. The particular method recommended in the Pine Australia Quality Manual (Pine Australia 1995) has been based on a system proposed for use in Europe. (CEN 1993). Hyne and Son's Tuan sawmill which produces Slash Pine structural products, implemented an output control system in November of 1995. On the 6th of December 1995 the Tuan Mill was the first in Australia to be approved by Pine Australia to produce the new "MGP" products. In June 1996 the results of seven months of output control testing were collected and analysed to determine product compliance and areas for potential refinement to Hyne and Son's grading process. This paper is a case study of the output control at the Hyne and Son Tuan mill and how it has been used to improve product quality and the grading process itself.

MATERIALS AND METHODS

A total of 3335 pieces of Hyne and Son structural Slash Pine were subjected to output control bending tests between the 2nd of November 1995 and the 18th of June 1996. Table 1. summarises the numbers, sizes, grades and types of timber product subjected to output control testing.

Table 1. Summary of Output Control Test Samples.

Grade	Product Type	Number Tested for Each Size				
		70 x 35	90 x 35	120 x 35	70 x 45	90 x 45
F4	Solid	403	161	5	5	20
MGP10	Solid	284	325	20	10	30
MGP12	Solid	282	337	20	10	30
MGP15	Solid	273	267	15	10	25
F14	Solid	20	75	-	-	10
F17	Solid	-	130	-	-	-
Reman.	Solid	100	35	-	-	-
F4	Finger Joint	50	25	-	-	-
F5	Finger Joint	234	70	-	-	-
F8	Finger Joint	30	24	-	-	-
Total		1676	1449	60	35	115

All specimens where subjected to standard bending tests as defined in AS/NZS4063 (Standards Australia 1992). The bending test rig used for the testing was purpose built by Hyne and Son for less than $5000. Measurements to allow calculation of the modulus of elasticity were taken on every specimen. When determining the design bending strength of timber, it is sufficient to use proof loads so that only enough specimens are broken to reliably estimate a 5 percentile strength. Proof loads were established in accordance with the requirements of the Pine Australia Quality Control Manual (Pine Australia 1995). This use of proof loads allowed the majority of test specimens to survive the testing unbroken and thus be returned to storage for sale.

ANALYSIS

The following analyses were undertaken,

i) Determination of Design MOE's and MOR's in accordance with AS/NZS 4063
ii) Monitoring of the mean MOE and 5%ile MOR in accordance with AS/NZS YYYY
iii) Regressions of Sample Length Vs Mean MOE
iv) Regressions of MSG settings Vs Design MOE, Design MOR & Characteristic MOR

RESULTS AND DISCUSSION

Tables 2 and 3 summarise the results of the AS/NZS 4063 analysis for Modulus of Elasticity and Modulus of Rupture in 35 mm thick framing, respectively.

Table 2. Modulus of Elasticity - AS/NZS 4063 Analysis

Size Width x Thickness	Grade	Number Tested	Modulus of Elasticity (MPa)		
			Mean	Actual Value	Design Value
70, 90 x 35	F4	564	8115	7830	6100
70, 90, 120 x 35	MGP10	629	10220	10140	10000
70, 90, 120 x 35	MGP12	639	13680	13590	12700
70, 90, 120 x 35	MGP15	555	16825	16730	15200
70, 90 x 35	F14	95	17780	17570	12000
90 x 35	F17	130	19070	18865	14000
70, 90 x 35	F4-FJ	64	8672	7609	6100
70, 90 x 35	F5-FJ	279	11740	10446	6900
70, 90 x 35	F8-FJ	54	13335	13215	9100

Table 3. Modulus of Rupture - AS/NZS 4063 Analysis

Size Width x Thickness	Grade	Number Tested	Modulus of Rupture (MPa)		
			Characteristic Strength	Actual Value	Design Value
70, 90 x 35	F4	564	17.4	7.4	4.3
70, 90, 120 x 35	MGP10	629	18.5	7.1	5.5
70, 90, 120 x 35	MGP12	639	27.7	10.9	9.5
70, 90, 120 x 35	MGP15	555	40.0	16.0	14.0
70, 90 x 35	F14	95	49.4	19.8	14.0
90 x 35	F17	130	56.2	22.6	17.0
70, 90 x 35	F4-FJ	75	16.7	6.6	4.3
70, 90 x 35	F5-FJ	304	18.8	7.5	5.5
70, 90 x 35	F8-FJ	54	23.6	9.4	8.6

Draft standard AS/NZS YYYY, provides a procedure for monitoring the structural properties of graded timber. This procedure involves a comparison between the actual test results and the target values determined from design stresses claimed for the product. Minimum sampling rates of 1 in 10000 are recommended by this standard. The sampling rate resulting from output control testing at Tuan is approximately 1 in 400. The comparison involves the mean MOE and the fifth percentile MOR. Tables 4 and 5 summarise the results of the analysis undertaken in accordance with AS/NZS YYYY. A quality report based on the AS/NZS YYYY analysis has been prepared and distributed to Hyne and Son customers. A copy is attached to this report as appendix A.

Table 4. Modulus of Elasticity - AS/NZS YYYY Analysis

Size Width x Thickness	Grade	No. Tested	Min. No. Required	Modulus of Elasticity (MPa)			% Diff Data - Target
				$E_{mean, data}$	$E_{mean, target}$	$0.94\ E_{mean, target}$	
70, 90 x 35	F4	564	5	8115	6100	5735	+41%
70, 90, 120 x 35	MGP10	629	29	10220	10000	9400	+9%
70, 90, 120 x 35	MGP12	639	21	13680	12700	11940	+15%
70, 90, 120 x 35	MGP15	555	15	16825	15200	14290	+18%
70, 90 x 35	F14	95	12	17780	12000	11280	+57%
90 x 35	F17	130	12	19070	14000	13160	+45%
70, 90 x 35	F4-FJ	64	4	8672	6100	5734	+51%
70, 90 x 35	F5-FJ	279	9	11740	6900	6486	+76%
70, 90 x 35	F8-FJ	54	5	13335	9100	8554	+56%

Table 5. Modulus of Rupture - AS/NZS YYYY Analysis

Size Width x Thickness	Grade	No. Tested	Min. No. Required	Modulus of Rupture (MPa)			% Diff Data - Target
				$R_{0.05, data}$	$R_{0.05, target}$	$0.91\ R_{0.05, target}$	
70, 90 x 35	F4	564	40	17.9	10.9	9.9	+80%
70, 90, 120 x 35	MGP10	629	73	19.1	14.3	13.0	+46%
70, 90, 120 x 35	MGP12	639	48	28.4	24.2	22.0	+29%
70, 90, 120 x 35	MGP15	555	36	40.9	35.1	31.9	+28%
70, 90 x 35	F14	95	33	52.0	35.1	31.9	+63%
90 x 35	F17	130	29	58.6	42.2	38.4	+53%
70, 90 x 35	F4-FJ	75	40	17.8	10.8	9.9	+80%
70, 90 x 35	F5-FJ	304	40	19.4	13.9	12.6	+54%
70, 90 x 35	F8-FJ	54	40	25.5	21.7	19.7	+29%

Between the 2nd of November 1995 and the 18th of June 1996, Hyne and Son has sampled and tested (bending & tension tests) a total of 3550 pieces of framing . A comparison of the Hyne testing to the Pine Australia - CSIRO study which lead to the establishment of the Pine Industry "MGP" grades is shown in Table 6. In summary, the bending tests done at Hyne and Son's Tuan mill in seven months is on average 10 times greater per grade per mill than was done in 1992 by the Pine Australia - CSIRO study.

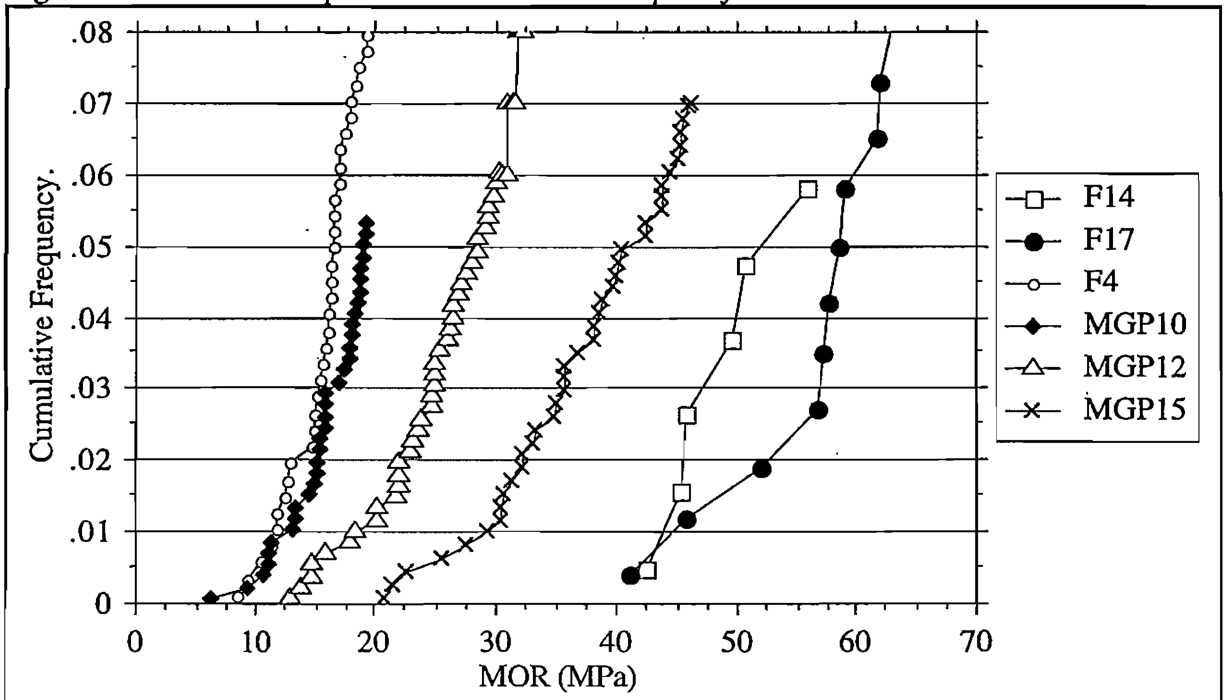
Table 6. Comparison of Hyne & Son Testing and Pine Australia - CSIRO Testing

Test Authority & Time	No. of Mills	No. of Bending Tests on 70, 90 and 120 x 35	No. of Grades Evaluated	Average No. of Tests per Grade per Mill
Hyne Nov'95-June'96	1	3185	9	354
Pine Aust.-CSIRO 1992	13	1375	3	35

Note: The nine grades tested by Hyne and Son are F4, MGP10, MGP12, MGP15, F14, F17, F4-FJ, F5-FJ and F8-FJ.

A graph of modulus of rupture versus the cumulative frequency function is shown in Figure 1.

Figure 1. Modulus of Rupture Vs Cumulative Frequency Function.



The relationship between graded length and the mean MOE of the 5 daily samples was investigated for 70x35 and 90x35 in each of the four main grades.ie. F4, MGP10, MGP12 & MGP15. The linear regression models below are those that were found to be statistically significant.

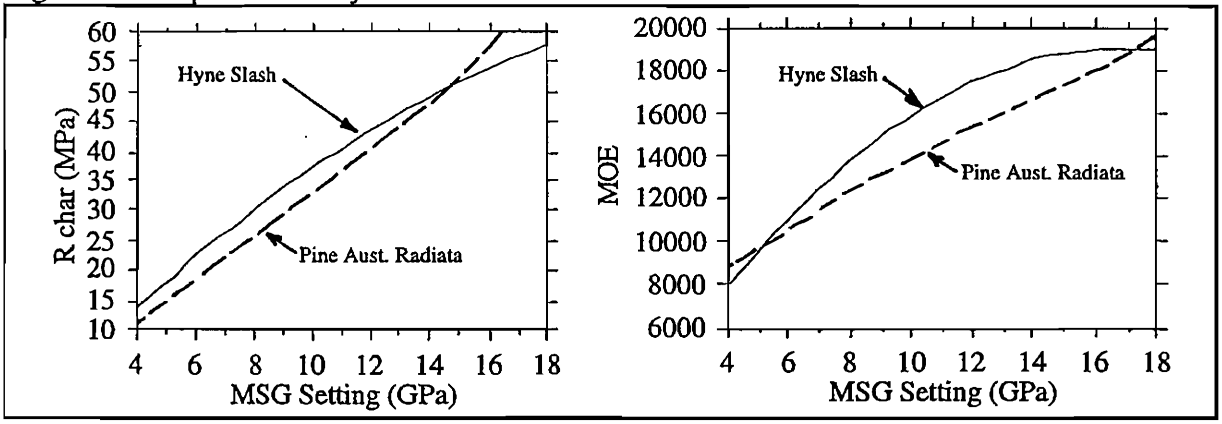
90x35	MGP10	Mean MOE (MPa) = 8652 + 277 x Length (m)
90x35	MGP12	Mean MOE (MPa) = 12053 + 438 x Length (m)
90x35	MGP15	Mean MOE (MPa) = 14991 + 457 x Length (m)
70x35	F4	Mean MOE (MPa) = 6248 + 447 x Length (m)

In each of the above models the percentage differences between the MOE for 6.0m lengths and the MOE for 2.4m lengths is, 11%, 12%, 10% and 22% respectively. The significant relationships above, are all positive indicating the general trend for increasing MOE as graded length increases. The relationships for the other four grade/size combinations investigated were also positive.ie. 70mm MGP10,12,15 & 90mm F4. This general relationship can be explained by considering the reduced probability, in longer lengths, that the low MOE point in the sample will be tested.

The relationship between MSG settings and the basic MOR, characteristic MOR and design MOE was established and is shown below. These relationships are compared in Figure 2 with the known relationships for radiata pine from the Pine Australia-CSIRO study.

R basic (MPa) = -2.67 + 2.13 x Setting (GPa) - 0.038 x Setting^2	R^2 = 0.987
R char (MPa) = -5.85 + 5.27 x Setting (GPa) - 0.095 x Setting^2	R^2 = 0.987
E design (MPa) = -47.9 + 2253 x Setting (GPa) - 66.5 x Setting^2	R^2 = 0.993

Figure 2. Comparison of Hyne Slash models with Pine Australia Radiata models



The results presented above are only applicable to the unique resource and processing characteristics associated with the Hyne and Son Tuan Mill. Any attempt to apply the above specific results to other timber grading operations is completely inappropriate.

CONCLUSIONS

1. The adoption of output control procedures in sawmills producing structural softwood will provide the following benefits.

i) A means of better controlling the structural properties of products
ii) Evidence of structural property compliance on a daily basis
iii) Test information suitable for completing analysis to AS/NZS YYYY
iv) A means of quantifying the difference between actual and claimed properties
v) A means of quantifying the effects of resource or process changes
vi) Savings in the costs of structural testing
vii) Immediate feedback about the quality of timber from particular consignments
viii) A sound information base to improve timber grading systems

2. The increasing implementation of output control systems by structural timber producers will ultimately lead to more efficient resource utilisation and increased designer confidence in the structural properties of timber products.

3. A positive relationship between MSG settings and length exists.

RECOMMENDATIONS

1. Producers of structural softwood products should seriously consider implementing output control systems.

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Appendix A.

QUALITY REPORT

THE STRUCTURAL PROPERTIES OF HYNE AND SON PINE FRAMING

Introduction

This report summarises the results of Hyne and Son's daily structural testing program from the 2/11/95 to the 18/6/96. A total of 3185 pieces of 35mm framing was tested. The results given below indicate the quality of Hyne and Son's pine framing products.

Product Specification

Hyne Product Specification PS 230 Pine Framing, including

AS1748 Mechanically Stress Graded Timber

AS2858 Timber-Softwood-Visually Stress Graded for Structural Purposes

Process Specifications

Hyne - Tuan No.1 Planer Operational Procedures - Doc. No. Q214-09-160

Hyne - Tuan Finger Joiner Operational Procedures - Doc. No. Q214-09-220

Independent Product / Process Audits

Pine Australia — Pine Australia Quality Control Program

Standards Australia — ISO 9002 Quality System Accreditation

Holmes McLeod Consult. Engs. — Certification of Finger Joint & HGP products

Evaluation & Monitoring Standards

AS/NZS 4063 Timber-Stress grade-Ingrade Strength and Stiffness Evaluation

AS/NZS YYYY Timber-Stress graded-Procedure for Monitoring Structural Properties

Pine Australia Quality Control Manual - Output Control Requirements

Results of AS/NZS YYYY Analysis of 35 mm Thick Framing

No. Tested	Bending Strength			Modulus of Elasticity		
	Grade	Target Strength (MPa)	Hyne - Target % Difference	Grade	Target Stiffness (MPa)	Hyne - Target % Difference
564	F4 (HGP7)	4.3	+80%	F4 (HGP7)	6100	+41%
629	MGP10	5.5	+46%	MGP10	10000	+9%
639	MGP12	9.5	+29%	MGP12	12700	+15%
555	MGP15	14.0	+28%	MGP15	15200	+18%
95	F14	14.0	+64%	F14	12000	+57%
130	F17	17.0	+53%	F17	14000	+45%
75	F4 - FJ	4.3	+80%	F4 - FJ	6100	+51%
304	F5 - FJ	5.5	+54%	F5 - FJ	6900	+76%
54	F8 - FJ	8.6	+29%	F8 - FJ	9100	+56%

Conclusion

The structural properties corresponding to "F" grades and the Pine Australia "MGP" grades, significantly underestimate the structural properties of Hyne Slash Pine framing. Measurements of framing strength and stiffness on a daily basis, allow Hyne and Son to quantify and control the margin of safety between the claimed properties of its framing products and the as-produced properties. In all grades Hyne products exceed the required strength and stiffness properties, some by up to 80%. Designers of timber structures using Hyne framing products can have confidence that these products will have reliable structural properties that exceed all strength and stiffness requirements.

Chris Robertson, Tuan Mill Manager — Geoff Stringer, Product Engineer — Dave Bennetts, Tuan Product Manager

Further Information: Please contact Dave Bennetts (071-218807) if you have any questions. 25/9/1996

LIMIT STATES DESIGN FOR TIMBER STRUCTURES

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ABSTRACT

This paper is concerned with the limit states design of timber structures, in particular, the limit states design of hardwood I-beam with trellis webs. In Australia, the design code for timber structures, known as the SAA Timber Structures Code, is undergoing a change from working stress design to limit states design format. This would undoubtedly be a challenge to design engineers after using the working stress design for so many years. For them to have a better understanding of limit states design, this paper attempts to provide a background and basic theory of limit states design. The application of limit states design to timber structures, in particular to timber I-beams with trellis webs, will be investigated. A procedure of limit states design for timber structures will be presented which includes modelling of loads and structural resistance (structural strength), selection of 'target' safety level and finally determination of load and resistance factors in the design format.

1 INTRODUCTION

A design procedure, in which some or all of the design parameters are treated as random variables and the reliability of structures can be numerically quantified, is known as reliability-based design (Li, 1995). Since the failure of the structure (or structural component) is generally defined as the violation of a limit state, the reliability-based design is usually expressed in a limit states design format, in which load and resistance factors are used to account for the required safety level of structures to be designed. In practice, reliability-based design is known as Limit States Design (LSD). The reliability-based limit states design format has following advantages:

(1) LSD method uses a more complete and realistic description of the actual conditions for structural design, such as modelling of loads and resistance, and for structural performance, such as ultimate limit state and serviceability limit state. The better understanding of the method provides designers on how structures are actually loaded and respond to loads, so that a more rational, realistic and efficient design may be produced;

(2) LSD procedure is information sensitive and provides a framework for new knowledge and development in engineering. By using load and resistance factors, it can accept new data related to loading, material properties etc., and it also acts to identify the limitations and deficiencies of present data for future research;

(3) The design format of LSD is simple (see below). Designers do not need to be directly involved with reliability analysis since this is implemented almost entirely at the design code development stage;

(4) The most important advantage of LSD method is the potential economic benefit since reliability techniques may be used in choosing the 'target' safety index in structural design so that an optimal balance between the total cost (including the construction, maintenance and the failure costs) and the safety can be achieved as shown schematically in Figure 1.

resistance. Therefore, in Equation (17) the only parameter that has significant effect on partial factors and hence, the design results, is the target safety index β_T. Obviously, it is more rational and sensible to use the optimal safety index as the target safety index, which will minimise the total cost of the structure. This is particularly so when both designers and users (clients) are more sensitive than before to the economical aspect of the structures to be built.

Taking the limit state function of Equation (3) as a simple example, the load and resistance factors γ_S, ϕ can be obtained, according to Equation (16) with i replaced by R or S respectively, β_T replaced by β_O, and using nominal values, as follows

$$\gamma_i = (1 - c_S \beta_o V_S)\frac{\mu_S}{S_n}$$

$$\phi = (1 - c_S \beta_o V_R)\frac{\mu_R}{R_n} \qquad (17)$$

When values of parameters of Equation (17) are available, the load and resistance factors, γ_S and ϕ, can be determined.

5 DESIGN OF TIMBER I-BEAMS WITH TRELLIS WEBS

5.1 Trellis Webbed I-Beams

In an economically driven society, any cost-effective building structure products might take substantial market share as long as the strength and serviceability requirements are guaranteed. Timber I-beams with trellis webs (see Figure 3) have the potential of achieving cost-effectiveness, and at the same time, structural adequacy if they are properly designed. As can be see from Figure 3, the beam has the following advantages:

1. The use of an I-section allows for the optimisation of the timber volume with increased sectional properties and efficient use of wood fibres;
2. It allows for the implementation of services required in residential apartments with little effect to the load bearing capacity of the member.
3. Perhaps the most important advantage is the potential economic benefit provided by the configuration of the beam.

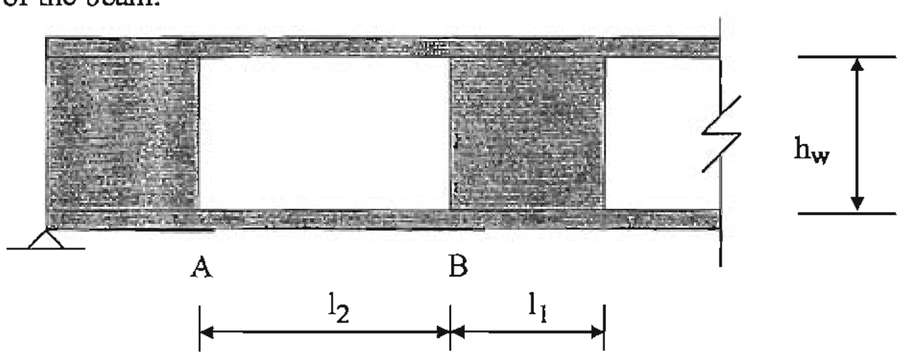

Figure 3 Trellis Webbed I-beams

5.2 Load and Resistance Models

The applied loads on timber floors are basically live loads which can be modelled as lognormal variables. Finite element analysis of the trellis webbed beam (Rodger and Li, 1996) shown that the most critical design parameter affecting the strength and serviceability of the beam is the distance between the webs, i.e., l_2 in Figure 3. Further study of the beam indicated that this design variable, l_2, is directly related to the shear stress at the glue line, which can be expressed as follows

$$\tau_S = \frac{(l_2 - b)w}{d} \tag{18}$$

where τ_s is the shear stress, the load effect produced by applied loads w in N/mm, b is a length parameter in mm and d is an area parameter in mm^2. Both b and d are constant and can be determined from experiment or computer simulation. From the analysis of Rodger and Li (1996), b and d may take 150 and 605 respectively.

The resistance of the beam, in this case is simply the shear strength of the glue line, τ_R, which is modelled as a lognormal variable too.

5.3 Safety Index

To evaluate the reliability of trellis webbed beams, a limit state function should be established. As shown above, the most critical design condition of the trellis webbed I-beam is the shear stress at the glue line. Therefore the limit state function for shear strength is

$$G = \tau_R - \frac{(l_2 - b)w}{d} \tag{19}$$

The reliability of the beam can be evaluated if all statistical data required are available. Assuming

$$\mu_w/w_n = 0.8, \qquad w_n = 1.5\ \text{kPa}, \qquad V_w = 0.3$$
$$\mu_R/R_n = 1.5, \qquad R_n = 1.0\ \text{MPa}, \qquad V_R = 0.2$$

the safety index of the beam can be calculated using equation (11), the results of which are shown in Figure 4.

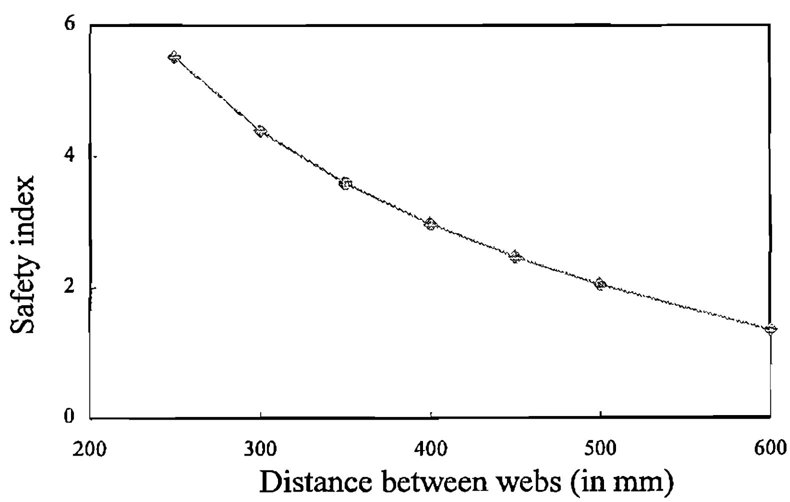

Figure 4 Safety index as a function of l_2

The optimal safety index can be determined using equation (14). To obtain the necessary data required in equation (14) a survey on the construction cost and failure cost is needed. Assuming initial cost coefficient $\alpha = 0.1$ and the relative failure cost $C_I = 1$, the optimal safety is $\beta_0 = 2.19$. As can be seen from Figure 5, the higher failure cost is the higher level of safety should be but when the cost is too high safety cannot be warranted.

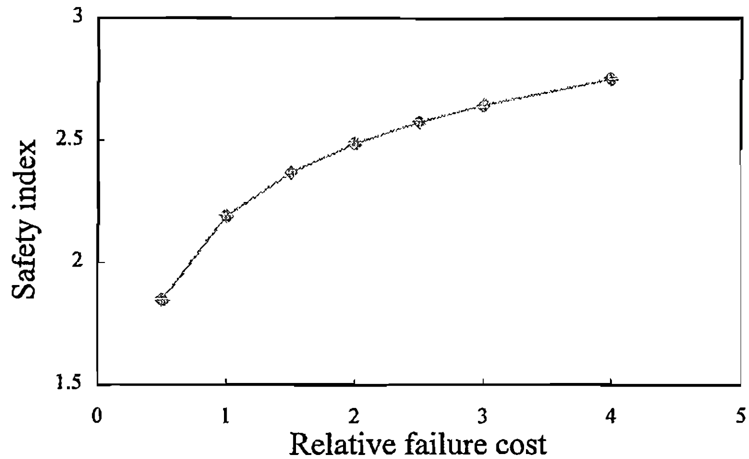

Figure 5 . Safety as a function failure cost

5.3 Design format

The limit states design format is as shown in equation (1). In practice, the key is to determine the load and resistance factors. If the above statistical data represent the uncertainties of trellis webbed I-beams, equation (17) can be used to calculate the partial factors which are $\gamma = 1.2$, $\phi = 0.9$.

6 CONCLUSION

To meet the challenge of the change from working stress design to limit states design of timber structures, the present paper has provided a background and basic theory of limit states design in the hope that a better understanding of limit states design would be gained. The application of limit state design to timber structures, in particular to timber I-beams with trellis webs, has been investigated. A procedure of limit state design for timber structure has also been presented.

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Finite Element Analysis of Timber I-beams with Trellis Webs

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Abstract

A two dimensional, plane stress finite element model was used to analyse the deflections and stresses of a timber I-beam with a trellis web occurring due to the service conditions commonly applied on flooring joists. The parameters affecting the serviceability and strength of the beam were examined. Through this analysis correlations between the design parameters and structural performance, such as the stresses and deflections were developed. The most critical parameter effecting the strength and serviceability of the trellis webbed beam was found to be the distance between the web sections. This finding will be verified by prototype testing at the next stage.

1. Introduction

Timber I-beams with trellis webs (refer to Figure 1.) offer an attractive alternative to conventional flooring joists due to the following advantages:

1. The use of an I-section allows for the optimisation of the timber volume with increased sectional properties and efficient use of wood fibres.
2. It allows for the creation of large spanning members, minimising the amount of bearing required at mid-span of large dwellings.
3. The use of the trellis webs allows for the implementation of services required in residential apartments with little effect on the load bearing capacity of the member.
4. Perhaps the most important advantage is the potential economic benefit provided by the configuration of the joist. By utilising timber shorts the material cost is significantly reduced.

With such advantages a substantial market share is apparent if a structurally adequate product can be developed. Therefore a full analysis of timber I-beams with trellis webs is desirable.

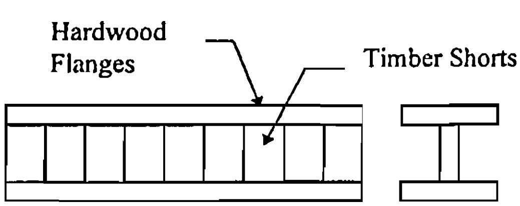

Fig. 1 Trellis Web Configuration

For trellis webbed I-beams the sudden change of sectional geometry creates similar problems to those experienced in the analysis of notches and holes in timber beams[1], [2]. For this reason, it is impossible to accurately evaluate the stresses in the beam using elementary elastic mechanics as they are irrespective of internal stressing arrangements. Thus the use of finite element analysis is necessary. Finite Element Analysis has been used in the analysis of other timber structures including wood poles[3], finger joints[4], glue-laminated beam-columns[5] and notched beams [1].

In this paper, the importance of the geometrical parameters most likely to affect the performance of the beam as a load bearing member will be studied. From this analysis an optimised configuration for both strength and serviceability will be established. Finite Element Analysis of the trellis webbed beam was carried out using the computer package STRAND 6.16[6]. Relevant timber properties were calculated in accordance with the Australian Timber Structures Code, AS1720.1[7].

The high level of durability required by a floor joist promotes the use of a phenol resorcinol glue joint. The allowable stress in the glue line is a crucial factor in determining the strength and serviceability of the member. This study focuses on the impact of different configurations on the deflection and the stress concentration at the web - webless transition. From this the limitations of individual parameters on the configuration can be determined.

2. Design Variables

Studies into built up timber beams such as plywood webbed beams[8] reveal that flange sizes can be developed using elementary mechanics. This relates to the lever arm action offered by flanges in an I configuration. Based on this assumption, flange depths and widths were defined.

To examine the influence of changes in geometry on the strength and serviceability of the trellis webbed beam the following parameters (refer to Figure 2.) were identified:

- the length of timber off cut to be used as a web section, $\mathbf{l_1}$;
- the clear distance between web sections, $\mathbf{l_2}$;
- the height of the web section, $\mathbf{h_w}$;

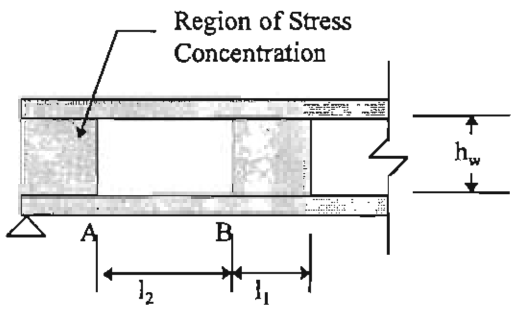

Figure 2 Geometric Parameters

The following structural responses were then checked:

- the comparative deflection, δ_{L2}, at points A and B;
- the total deflection, δ_T, at the mid-span;
- the stresses at the sectional changes.

3. Finite Element Model

Finite element analysis is a mathematical process where algebraic equations are generated in relation to the structure being modelled. The advantage of such a process is that it allows for the development of equations relating to the geometric constraints of a system with respect to boundary conditions. The model chosen for the trellis webbed beam is two dimensional plane stress. The continuous lateral restraint provided by the flooring system effectively minimises movement in the z axis, thus analysis in only the x and y axes is necessary. Plane stress analysis is completed assuming a thin plate is loaded at the boundary and parallel to the plane of the plate. The load is assumed to be uniformly distributed across the thickness of the member. All of these conditions correspond to the service conditions of the trellis webbed I-beam.

The finite element method can be summarised by following steps:

1. Divide the structure into elements;
2. Formulate element properties (this is particularly important in timber due to its orthotropic nature);
3. Assemble elements as a mesh (ie. develop complementary function relating to the geometry of the structure);
4. Apply known loads (ie. create particular integral for loading characteristics);
5. Specify supporting arrangement and define degrees of freedom for nodes;
6. Solve equations, using element strains established from deflections.

The orthotropic nature of timber must be modelled accurately for the production of reliable results. Since shear deflection is a function of the shear modulus, G, and for timber

$$G = E/15$$

where E = Modulus of Elasticity, the shear deflection in timber is critical. This is even more important when the web member consists of an inferior product. Milner[9] describes the compliance relationship between stress and strain in terms of axes L, T, and R as being $\varepsilon = C\sigma$, where ε is the strain and C is the compliance matrix:

$$C = \begin{bmatrix} \frac{1}{E_L} & -\frac{\nu_{TL}}{E_T} & -\frac{\nu_{RL}}{E_R} & 0 & 0 & 0 \\ -\frac{\nu_{LT}}{E_L} & -\frac{1}{E_T} & -\frac{\nu_{RT}}{E_R} & 0 & 0 & 0 \\ -\frac{\nu_{LR}}{E_L} & -\frac{\nu_{TR}}{E_T} & \frac{1}{E_R} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{LT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{TR}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{RL}} \end{bmatrix}$$

Where : L, T and R represent longitudinal, tangential and radial directions respectively.

Typical values of the prescribed constants for timber are

E_R=0.1E_L E_T=0.05E_L G_{LT}=0.06E_L
G_{LR}=0.075E_L G_{RT}=0.018E_L ν_{LR}=0.40
ν_{RL}=0.04 ν_{LT}=0.40 ν_{TL}=0.02
ν_{RT}=0.50 ν_{TR}=0.25 (1)

For plane stress analysis ε_{TT}=0, ε_{TR}=0 and ε_{TL}=0.

To gain the elasticity matrix for bilinear quadrilateral elements the above predefined matrix must be inverted and have the radial coefficients multiplied through. The resulting elasticity matrix is given by:

$$C^{-1} = \begin{bmatrix} \dfrac{E_L}{1-\nu_{RL}.\nu_{LR}} & \dfrac{\nu_{RL}.E_L}{1-\nu_{RL}.\nu_{LR}} & 0 \\ symmetric & \dfrac{E_R}{1-\nu_{LR}.\nu_{RL}} & 0 \\ & & G_{RL} \end{bmatrix}$$

where E_L = Longitudinal Modulus of Elasticity
E_R = Radial Modulus of Elasticity
ν_{RL}= Poison's ratio = 0.04
ν_{LR}= Poison's ratio = 0.40

STRAND 6.16 provides its own orthotropic input module which directly corresponds to the elastic matrix defined above. However the use of a plate for stress analysis requires the property input to be a function of the thickness of each plate. Hence in this study, the thickness is incorporated in the STRAND module. Also the directions L and R are replaced for the more conventional x and y axes.

The proposed trellis webbed I-beams are to be constructed of Australian Hardwood. The timber chosen to be modelled is a typical F17 hardwood whose engineering properties are detailed by AS1720.1 as being

E_x = 14 000 MPa
G_{xy} = 930 MPa
ν_{xy} = 0.4 (2)

The subsequent values of E_y and ν_{yx} can be determined by the relationships previously described in Eqn (1).

4. Beam Model

The beam design was based on the composite construction of common hardwood sections designated by the Timber Promotion Council. In order to create structurally sound members the flanges were designed using the lever arm method. This involves the determination of the stress in the tensile member which in the majority of cases is critical for timber. The tensile stress as a function of loading, f_t, was then compared to the 'k' factored value of F_t in accordance with AS1720.1. The resultant calculations suggested a flange size of 90x35 mm for adequate strength and serviceability with a live load of 1.5 kN/mm^2 acting over a 1000 mm tributary area.

The web depth and thickness were initially determined as a function of the allowable span/depth ratio. A common range for the span depth ratio of a floor joist is 13 to 18[8]. To maintain the appropriate ratio, the depth of the web section was limited to either 90 mm or 120 mm. The width of the web section was then checked for adequate shear stress at its most concentrated point, ie. at the positions of bearing. The shear stress was then calculated

$$f_s = \frac{V.Q}{I.b} \qquad (3)$$

where all dimensions relate to the fully webbed I-section.

The value of f_s was compared to the factored F_s to ensure $f_s \leq F_s$. The corresponding value for web thickness was 45 mm. This was only a trial value as the effect of the non consistency of the web would be accounted for in the finite element analysis.

In this study, the web and flange sections remained constant to allow the variation of other parameters. However both could be altered subject to a change of web depth.

The trellis webbed models were constructed of a series of bilinear quadrilateral elements, representing separate properties for the flange and web sections. Elements were typically of the dimensions 11.67x25 mm in the flange and either 22.5x25 mm or 30.0x25 mm for the 90 and 120 mm web respectively. This varied in the x direction depending on the actual dimensions to be used, however these differences were accounted for by the package STRAND. Table 1 represents the overall dimensions of the 17 models that were analysed. All models were of span 3.0 m and parameters h_w, l_1 and l_2 refer to Figure 2.

Uniformly distributed loading conditions were simulated by applying nodal forces based on the 1.76 N/mm^2 load over the tributary area. The same process is completed for an increased load of 3.0 N/mm^2 which produces twice the moment in the member than the application of a 1.5 N/mm^2 live load.

Table 1. Specimen Dimensions

Specimen	h_w	l_1	l_2
1	90	180	172.5
2	120	180	172.5
3	90	180	290
4	90	224	172.5
5	90	258.3	290
6	90	200	267
7	90	150	206.25
8	90	100	190
9	90	125	234.4
10	90	250	208.3
11	120	250	300
12	90	250	437.5
13	120	250	666.7
14	90	213.1	185
15	120	270	185
16	90	345.83	185
17	120	168.8	185

Lateral support to the compression flange was modelled using plane stress which assumes the restriction of all nodes to move in the z direction or rotate about either the x, y or z axis. This assumption holds as long as sufficient support is provided to the compression flange. This is the case for floor joists.

5. Results

From the finite element analysis of the models previously specified, data relating to the relative deflection between points A and B (refer to Figure 2), the maximum shear stress, τ_{xy}, along the glue line and the total deflection of the beam was obtained and summarised in Table 2.

Typical deflections occurring between the webless sections in the trellis webbed beam can be seen in Figure 3. This section is representative of specimen 11 under loading where shear stress contours are displayed. The cantilever action experienced due to the web non existence (refer to Figure 3) together with the influence of the shear stress along the flange-web glue line is perceived to be a mode of failure. These patterns are typical for each section although the degree of concentration differs depending on geometric variables. As may be expected, more attention was paid to the plates closest to the flange-web and web-webless boundaries.

Table 2. Finite Element Results

	Load N/mm	$\tau_{xy.}$ MPa	δ_{L2} mm	δ_T mm
1	1.76	0.9338	0.8464	3.8889
	3.0	1.5917	1.4428	6.9182
2	1.76	0.8123	0.7369	3.2538
	3.0	1.3559	1.2227	5.4630
3	1.76	1.2856	1.8757	5.1753
	3.0	2.1914	3.1972	8.8216
4	1.76	0.9432	0.8330	3.8764
	3.0	1.6086	1.4207	6.6123
5	1.76	1.2708	1.7896	4.6646
	3.0	2.1661	3.0504	7.9510
6	1.76	1.2241	1.6209	4.8117
	3.0	2.0864	2.7629	8.2017
7	1.76	1.0373	1.1179	4.5375
	3.0	1.7681	1.9055	7.7344
8	1.76	1.0862	1.5596	7.5765
	3.0	1.9563	2.8077	13.638
9	1.76	1.0965	1.3724	4.9837
	3.0	1.861	2.3283	8.4398
10	1.76	1.0556	1.0758	4.0645
	3.0	1.7912	1.8263	6.9005
11	1.76	1.0471	1.6478	3.8890
	3.0	1.7848	2.8087	6.6290
12	1.76	1.6585	3.6651	5.5259
	3.0	2.8270	6.2473	11.123
13	1.76	1.8316	7.2118	8.8591
	3.0	2.7254	12.262	14.606
14	1.76	0.9857	0.9104	3.9320
	3.0	1.6803	1.5518	6.7022
15	1.76	0.8941	0.7369	2.9190
	3.0	1.5241	1.2568	4.9755
16	1.76	0.9675	0.8550	3.6018
	3.0	1.6492	1.4574	6.1394
17	1.76	0.8039	0.7839	3.3171
	3.0	1.3702	1.3362	5.6541

Initially the data from all specimens was manipulated and graphed to develop any apparent correlations between various parameters. To obtain all possible correlations from the data each geometric parameter was graphed against the shear stress, τ_{xy}, total deflection, δ_T, and the relative deflection, δ_{L2}, at webless sections (ie. the deflection occurring over the length l_2). Since the number of webless bays in the beams differed, the stresses and deflection of webless sections were checked at the bay positioned closest to the bearing end of the beam (refer to Figure 2).

Figure 3. Deflection over l_2, δ_{L2}

Each of the parameters l_1 and l_2 were plotted against relative deflections and shear stress. However, because of the limited height differentiation, only two different web depths were examined. The effect of the alteration of height will be discussed but is not able to be graphed against the resultant deformations.

6. Observations

By examination of the output data it is apparent that a direct relationship exists between the deformations and stresses of the trellis webbed beam and the parameter l_2. Initially the effect that each variable has on the outcome of the analysis must be considered, from this refined data sets can be developed.

Although the limited alteration of height does not allow a correlation to be developed between the parameter h_w and the deflections and stresses, a direct comparison of the effect on a beam with an increased depth can be made. The data collated indicates that an increase in the height of a web member directly causes a reduction in the shear stress τ_{xy}. Also shown is a decrease in the overall deflection of the beam. Thus depending on the allowable space for the joist to be implemented, a deeper web could be used to reduce the deflection and stresses. By using a deeper web the increase in cost is relatively small compared to the use of longer web sections because the amount of glue being used is the same with an increased strength and serviceability.

Data relating to the alteration of the length of the web section, l_1, reveals that no direct correlation between the deflections and stresses and the parameter l_1 (refer to Figure 4). In all cases the variable having the most effect on the deflection is the distance between web sections, l_2. Further study reveals that if the ratio l_1:l_2 becomes greater than 1:1.75 then the correlation appears to take a logarithmic form although regression analysis revealed that the standard deviation vastly increased, becoming too large to assume any predictable correlation. Alterations in the correlation of deflections and stresses become apparent when (1) the ratio l_1:l_2 exceeds 1:1.75, and (2) the depth of the web is altered. By limiting the values of parameters within the specified range an appropriate relationship can be found.

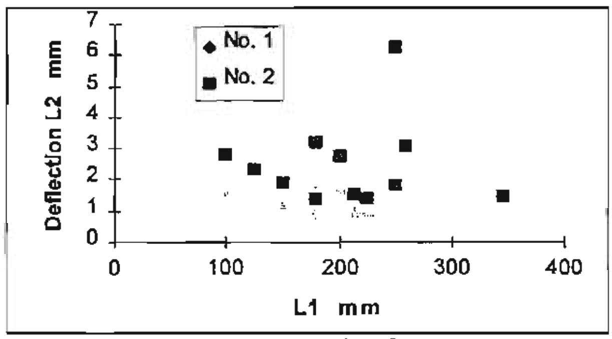

Figure 4 L_1 Vs δ_{L2}

All measurements taken at bay AB (see Fig. 2)

where No 1.= δ_{L2} for 1.76 N/mm loading

No 2.= δ_{L2} for 3.0 N/mm loading

By omitting specimens 2, 8, 11, 12, 13, 15 and 17 a clear relationship between the parameter l_2 and the deflections and stresses of the beam can be seen (see Figures 5 and 6). The above mentioned specimens all have a non compliance with the defined specifications.

Results of FEA for all remaining specimens showed a very good correlation between the parameter l_2 and the stresses and deflections determined. The data for l_2 Vs Total Deflection, δ_T are slightly more skewed. This is believed to be a function of the number of bays existing in the member (the number of bays corresponds directly to both the lengths l_1 and l_2). The number of webless bays is determined by:

$$3000 = n\left[l_1 + l_2\right] + l_1 \qquad (4)$$

where:

n = number of webless bays;

l_1, l_2 = prescribed dimensions (see Figure 2.)

Regression analysis[10] is commonly employed by engineers to develop empirical relationships between data sets. By quantifying the identified parameters, δ_{l2} and τ_{xy} relative to the distance l_2 an association between the shear deflection and shear stress can be established.

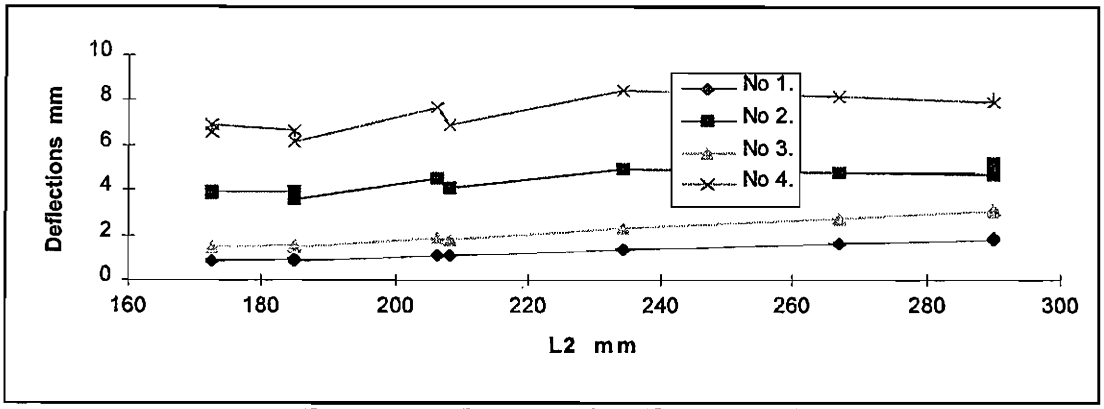

Figure 5 Deflection Vs l_2 ($h_w = 90$ mm)

where :

No 1. = δ_{L2} for 1.76 N/mm loading at bay AB (see Fig. 2)   No 2. = δ_T for 1.76 N/mm loading at midspan

No 3. = δ_{L2} for 3.0 N/mm loading at bay AB   No 4. = δ_T for 3.0 N/mm loading at midspan

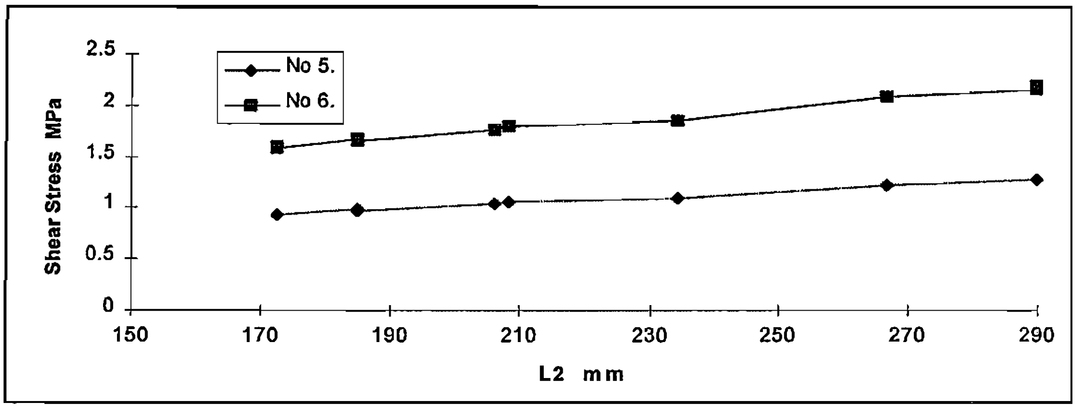

Figure 6 Shear Stress Vs l_2 ($h_w = 90$ mm)

where :

All measurements taken at the end bay (see Fig. 2)

No 5. = τ_{xy} for 1.76 N/mm loading   No 6. = τ_{xy} for 3.0 N/mm loading

Analysis of the relationship of Deflection over l_2, δ_{L2} Vs l_2 under the load of 1.76 N/mm reveals a linear correlation which can be expressed as:

$$l_2 = 114.0070\delta_{L_2} + 80.899 \quad (5)$$

Under the load of 3.0 N/mm this relation becomes:

$$l_2 = 66.9020\delta_{l_2} + 80.9802 \quad (6)$$

Equations 5 and 6 demonstrate a similar constant (80.94) and a similar low standard deviation. Such a relation reveals that a general mathematical expression can be developed for l_2 as a function of the deflection, δ_{L2}:

$$l_2 = \frac{200.68}{UDL_{(N/mm)}}\delta_{L_2} + 80.94 \quad (7)$$

The same mathematical analysis can be carried out on the shear stress, τ_{xy}, due to its high correlation (as seen in Figure 6). For a load of 1.76 N/mm the value of l_2 corresponding to the shear stress τ_{xy} is:

$$l_2 = 343.8456\tau_{xy} - 150.2617 \quad (8)$$

For a load of 3.0 N/mm the shear relative to l_2 is:

$$l_2 = 201.6844\tau_{xy} - 149.8834 \quad (9)$$

Again analysis reveals that l_2 is a function of the shear stress with respect to the loading applied. Equation 10 can therefore be developed from equations 8 and 9 and the corresponding loading arrangement.

$$l_2 = \frac{605.11}{UDL_{(N/mm)}}\tau_{xy} - 150.07 \quad (10)$$

These formulae can now be used to determine the dimension l_2 with respect to the allowable shear stress in the glue line, or the permissible shear deflection over the webless section. These relations are only valid for the dimensions specified in Figure 7, and where $l_1:l_2 < 1:1.75$.

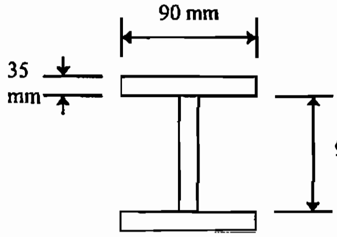

Figure 7 Specification of section dimensions

From the analysis it was found that, for an appropriate stress level the strength of the member is adequate, however the serviceability limit may be exceeded. It is therefore important to consider the overall deflection as a function of l_2.

The data for l_2 and δ_T exhibits a lower correlation coefficient of 0.86. However Devore(10) stated that this is an adequate correlation. The equations developed for 1.76 N/mm loading is:

$$l_2 = 73.26508\delta_T - 97.8743 \qquad (11)$$

while for a 3.0 N/mm loading:

$$l_2 = 43.76178\delta_T - 104.5841 \qquad (12)$$

Equations 11 and 12 show a larger standard deviation but can be used to construct the following relation between l_2 and δ_T:

$$l_2 = \frac{130.12}{UDL_{(N/mm)}}\delta_T - 101.23 \qquad (13)$$

The required distance between web sections can now be developed relative to loading using equations 7, 10 and 13. The value of l_2 is chosen as the minimum given from the three equations with respect to the limits imposed by the glue type and serviceability requirements.

7. Conclusions

It has been shown that timber I-beams with trellis webs could have a substantial market share if strength and serviceability limits can be guaranteed. Finite element analysis has been applied in the consideration of variables deemed to be critical in the beams design. This type of analysis was selected due to the inapplicability of elementary beam mechanics to model sectional alterations. Three design variables, h_w, l_1, and l_2 were selected for investigation of their impact on the shear stress, τ_{xy} and deflections, δ_{L2} and δ_T of the beam.

The results of the FEA has demonstrated that the most critical parameter for the design of trellis webbed beams is l_2, the distance between webs. It has also revealed that the variable l_1 has little effect on the strength and serviceability of the member. However the analysis showed that results become less reliable once a $l_1:l_2$ ratio exceeds 1:1.75. From regression analysis, a functional relationship has been developed between the parameter l_2 and the shear stress, deflections and the applied loads. This is advantageous as members can be designed against the allowable deflection or the maximum stress maintainable in the glue line. Variations in web height incurred a reduction in both stresses and deflections, although the permissible span depth ratios limit the use of the height as a determining factor.

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DETERMINATION OF DESIGN STRENGTHS FOR TOOTHED METAL NAIL PLATES IN SLASH PINE

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ABSTRACT

Current design strengths for toothed metal nail plates in Slash Pine are the same regardless of the structural grade. A testing program involving four slash pine grades and three reference species, plated with Gang-Nail GNQ plates, in two different joint configurations was undertaken to examine the relationship between mean product density and tooth design strength. Three methods of deriving design values where investigated, including the current Australian Standard, the 1996 revision of this standard and the CSIRO proposed "greybox" method. Models for estimating basic working loads per tooth, based on mean product density where determined. The current species based system of assigning tooth design strengths was found to be overly conservative for the high grades of slash pine and unconservative for the low grades. Providers of engineering design information for toothed metal nail plates should consider adopting grade based design strengths or design models for estimating tooth strength based on mean product density.

INTRODUCTION

One of the most successful methods of joining timber is through the use of a toothed metal nail plates. This type of connector is most commonly used in the fabrication of roof trusses. The design of timber joints using this connector requires knowledge of the toothed plates resistance to load. The establishment of design strengths for this type of connector has been traditionally based on documents like AS1649-1974 "Determination of Basic Working Loads For Metal Fasteners For Timber." This document defines standard test assemblies and outlines derivation methods for the basic working load of individual teeth within the plate. The testing involves the measurement of joint displacement under load as well as the ultimate failure load of the joint. Loads at 0.8mm displacement and ultimate loads are then both used to derive the basic working loads. The loads per tooth from this derivation can then used by designers to size the plates for particular load situations. A draft revision of AS1649, DR83020 (Standards Australia 1983), has omitted the need to establish basic working loads using loads corresponding with 0.8 mm displacement. DR83020 has recently been superseded by a public comment draft of this document, DR96286 (Standards Australia 1996). These above mentioned standards all encourage sampling on a species basis rather than on an individual product basis. As a result most sampling for establishment of tooth design values has sought to test timber which has an average density representative of the species. This in turn has led to design strengths being assigned to species rather than particular products. A reliability based derivation method for the strength of connectors, known as the CSIRO "greybox" connector standard, has also recently been proposed. (CSIRO 1995) This document is a significant step forward as it attempts to provide a reliability based method, which parallels the approach now taken with timber design values through AS/NZS4063. (Standards Australia 1992)

The design of wood metal joints, particularly dowelled connectors like nails, bolts and screws, has been the subject of considerable international research over the last ten or so years. The results of much of this work has led to the adoption in the USA and Europe of the "Yield Theory" for connector design. One assumption in this theory is that the resistance of the wood to a loaded connector is proportional to the density of the wood. This assumption has been validated, even for Australian timbers, and yet no move to introduce a yield theory approach within Australian timber design codes has been pursued. A method for use by designers has been previously recommended.(Stringer 1993). Does a relationship between the wood density of Slash Pine and the tooth strength of metal plate connectors exist?

The strength of joints fabricated using toothed metal plate connectors in Slash Pine has been investigated by a number of organisations (CSIRO, Gang-Nail, Hyne and Son) over many years. The wood sampled for these studies, the type of plates, test configurations and loading methods have all varied. The results from some of this work has lead to the current Gang-Nail design recommendations. ie. an allocation of a JD5 joint group to Slash Pine, with a basic working load of 115 N/tooth.(Gang-Nail 1991) Such a joint group is intended to be used by truss designers regardless of the particular stress grade or general wood quality. For Radiata Pine Gang-Nail recommendations suggest that a JD4 joint group may be used where heart is excluded in visually stress graded timber.(Gang-Nail 1992) In the design of bolted, nailed and screwed connections similar recommendations have been made for Slash Pine which is free of pith. (TRADAC 1992) Hyne and Son has recently extended its range of structural Slash Pine products to include the following grades. ie. F4(HGP7), MGP10(F5), MGP12(F8), MGP15(F11), F14 and F17. Table 1 summarises these products, mean densities and the seasoned joint groups assigned by AS1720.2 (Standards Australia 1990), Hyne & Son and Gang-Nail. Across these grades a range of densities exist and some truss fabricators have expressed an interest in taking advantage of any strength - density relationship to improve plate efficiencies instead of using a single joint group rating across all Slash Pine products. (Wilkinson 1995) These fabricators firmly believe that the higher grades of Slash Pine are stronger, not weaker than heart free Radiata Pine and are requesting changes to design values to assist them in designing more cost efficient joints. For instance, the density of seasoned Victorian Ash is only 650 kg/m^3 and yet it has a JD3 rating with a basic working load per tooth of 180 newtons, while the three highest Slash Pine grades have mean densities greater than 650 kg/m^3 and yet working loads per tooth are limited to 115 N/tooth.

Table 1. Summary of Hyne Products, Mean Densities and Joint Groups

HYNE Framing Products	Mean Density kg/m^3	Seasoned Joint Group			Basic Working Load (Newtons per Tooth) in GNQ plates.
		Hyne & Son (Nails, bolts, screws)	AS1720.2 (Nails, bolts, screws)	Gang-Nail (Toothed Plates)	
F4 (HGP7)	560	JD 5	JD 4	JD 5	115
MGP10 -F5	580	JD 5	JD 4	JD 5	115
MGP12 -F8	635	JD 4	JD 3	JD 5	115
MGP15 -F11	680	JD 3	JD 3	JD 5	115
F14	710	JD 3	JD 3	JD 5	115
F17	745	JD 3	JD 3	JD 5	115

Note: Hyne and Son have adopted TRADAC recommended joint groups for Slash Pine due to the presence of some low density juvenile wood in F4, F5 and F8.

The joint group designator JD, is used only to separate groups of timbers with common tooth strengths. Joint grouping for the purposes of plated joint design is a different system from that used for nailed, screwed or bolted joint design defined in AS1720. It was decided by Hyne and Son to investigate the actual tooth strengths for each grade of Slash Pine and to see if a suitable relationship for design purposes existed between wood density and tooth strength.

MATERIALS AND METHODS

In consultation with Gang-Nail Australia and a number of Gang-Nail fabricators, Hyne and Son undertook the test program summarised in Table 2. The parallel-to-grain and perpendicular-to-grain test configurations were the same as those used in another recent study. (Mackenzie & McNamara 1994). The Slash Pine and Hoop Pine used in the study was collected from timber produced at Hyne and Son's Tuan sawmill. Hoop Pine was included in the study as a reference species and because Hyne and Son produce a range of structural Hoop Pine products. The Slash and Hoop Pine were mainly backsawn, particularly the higher grades, with lower grades having some quartersawn sections. The other timbers used in the study were collected from commercially available structural timber. Victorian Ash and Radiata Pine were also included in the study as reference species to assist in interpreting the results. These timbers contained a representative portion of quartersawn and backsawn sections. The timber purchased as F17 Victorian Ash was confirmed (Cause 1996) as "southern Australian ash type Eucalypts", with the samples closely matching Eucalyptus delegatensis (Alpine Ash). All but 24 teeth on each end of the plates were removed and the plates pressed on to the timber. The prepared test specimens were then placed in the Hyne and Son tension test rig and loaded until failure. Individual test specimens were manufactured from the one piece of timber, no mixing of specimen components was undertaken. Growth ring width, growth ring orientation, pith presence and any other significant wood feature within the specimens were recorded.

Table 2. Hyne and Son - Gang-Nail Plate Test Program.

Species	Grade	Test Type	No. Tested
Slash Pine	F4 (HGP7)	Parallel-to-Grain	19
Slash Pine	MGP10-F5	Parallel-to-Grain	25
Slash Pine	MGP12-F8	Parallel-to-Grain	30
Slash Pine	MGP15-F11	Parallel -to-Grain	25
Victorian Ash	F17	Parallel-to-Grain	20
Radiata Pine	F11	Parallel-to-Grain	20
Hoop Pine	Clear	Parallel-to-Grain	22
Hoop Pine	Pith-in	Parallel-to-Grain	20
Slash Pine	F4 (HGP7)	Perpendicular-to-Grain	20
Slash Pine	MGP10-F5	Perpendicular-to-Grain	20
Slash Pine	MGP12-F8	Perpendicular-to-Grain	20
Slash Pine	MGP15-F11	Perpendicular-to-Grain	30
Victorian Ash	F17	Perpendicular-to-Grain	21
Radiata Pine	F11	Perpendicular-to-Grain	20
Hoop Pine	Clear	Perpendicular-to-Grain	20
Hoop Pine	Pith-in	Perpendicular-to-Grain	20

RESULTS AND DISCUSSION

The full results of this study are given elsewhere. (Stringer 1996) The three standards available for analysing the test data were used and an indication of the relativity between these different test standards is shown in Table 3. Loads at a 0.8 mm displacement where not recorded and as such the required AS1649 analysis of these loads was not undertaken.

The analysis methods result in different basic working loads. The AS1649 and DR96286 methods give fairly similar results while the CSIRO "greybox" method gives basic working loads which are about 12% lower. The CSIRO method is still in the course of development, (Folienti 1996) with the size of factors to be used in the derivation equations still to be finalised.

Table 3. Ratio of Basic Working Loads derived from different test Standards.

Test Type	No.	Ratio of DR96286 to AS1649-1974	Ratio of CSIRO"Greybox" to AS1649-1974
Perpendicular-to-grain	171	1.00	0.89
Parallel-to-grain	181	0.95	0.87
Perpendicular & Parallel	352	0.97	0.88

If the parallel-to-grain results for Slash Pine are examined then it is possible to develop expressions for basic working loads (BWL) as a function of mean density (MD). The basic working loads for each of the four Slash Pine grades are correlated to the mean densities of each grade sample, to produce the following design models.

Linear Regression

AS1649	BWL (N/tooth) = -85.86 + 0.327 x MD (kg/m^3)	R^2=0.85
DR96286	BWL (N/tooth) = -20.15 + 0.221 x MD (kg/m^3)	R^2=0.98
CSIRO "Greybox"	BWL (N/tooth) = -54.16 + 0.251 x MD (kg/m^3)	R^2=0.74

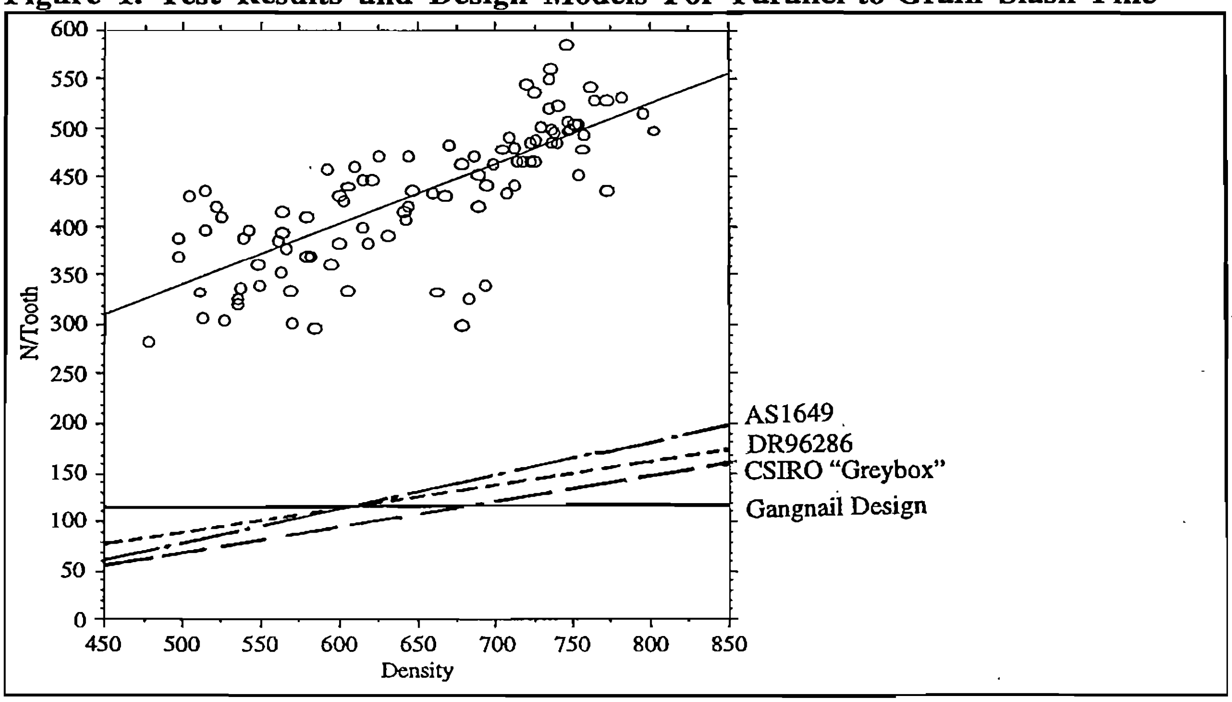
Polynomial Regression

AS1649	BWL = 1045 - 3.23 x MD + 0.327 x MD^2	R^2=0.97
DR96286	BWL = 256 - 0.65 x MD + 0.001 x MD^2	R^2=0.99
CSIRO "Greybox"	BWL = 1039 - 3.19 x MD + 0.003 x MD^2	R^2=0.92

The variation in test results is known to increase as the density decreases. The above models take this variation into account as the models are based on design values which have already been penalised for variation. The actual test results for parallel-to-grain Slash Pine (all four grades) are shown in figure 1, together with the linear expressions above and the current Gang-Nail design curve for Slash Pine which does not consider product grade or density. The linear regression model best representing the test data is,

Failure Load (N/tooth) = 32.95 + 0.616 x Density (kg/m^3)   R^2=0.58

Figure 1. Test Results and Design Models For Parallel-to-Grain Slash Pine



This graph indicates that the current design values recommended by Gang-Nail are likely to be conservative for the higher density Hyne and Son grades and slightly unconservative for the Hyne and Son F4 grade. Table 4 compares the predicted design values of Hyne products using the linear regression models with the current design values recommended by Gang-Nail.

A summary of the design values for the reference species included in the study compared to MGP15 Slash Pine is shown in table 5. An examination of the basic working loads derived from the current Australian standard AS1649, indicates that the species based system of allocating basic working loads for plate connectors is conservative for Slash, Radiata and Hoop Pine.

Table 4. Basic Working Loads - Parallel-to-Grain

HYNE Framing Products	Mean Density kg/m^3	Basic Working Loads Parallel-to-grain (Newtons per Tooth) Gang-Nail GNQ plates.			
		AS1649 Design Model	DR96286 Design Model	CSIRO "Greybox" Design Model	Current Design Values
F4 (HGP7)	560	97	104	86	115
MGP10-F5	580	104	108	91	115
MGP12-F8	635	122	120	105	115
MGP15-F11	680	137	130	117	115
F14	710	146	137	124	115
F17	745	158	144	133	115

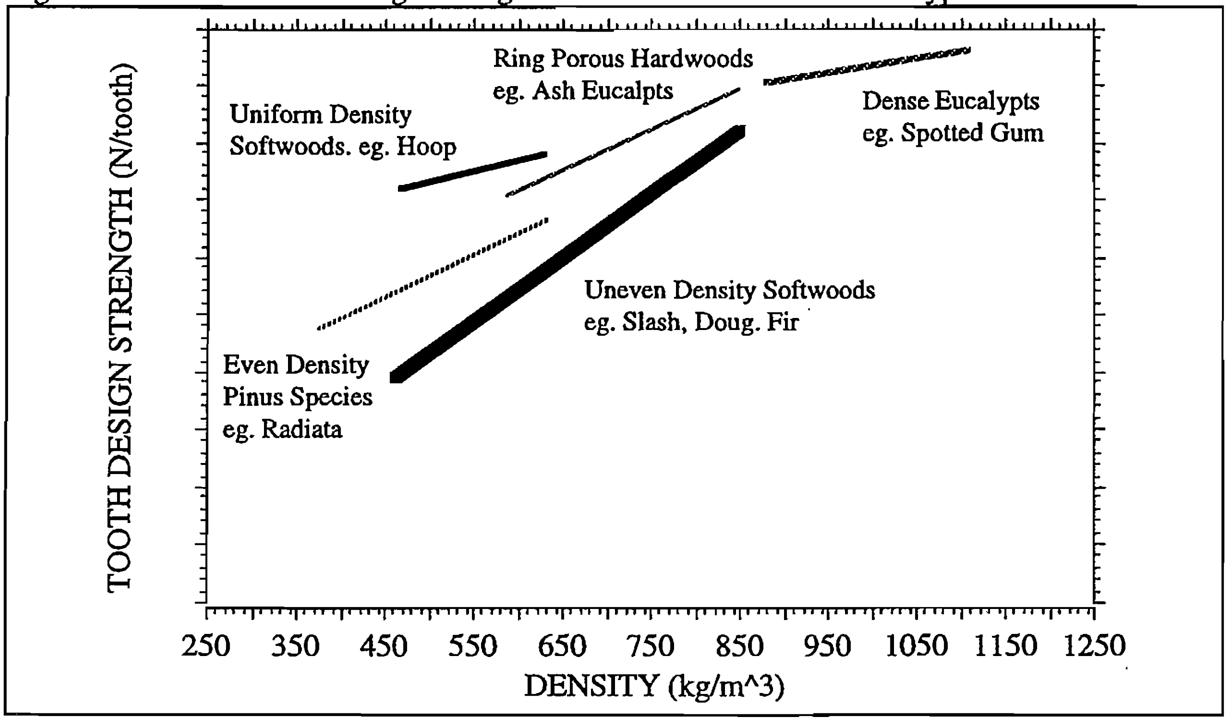
Table 5. Reference Species Results - Parallel-to-Grain

Species	Grade	No.	Mean Density kg/m^3	Basic Working Loads Parallel-to-grain (Newtons per Tooth) Gang-Nail GNQ plates.				Gang-Nail Joint Group
				AS1649	DR96286	CSIRO Greybox	Gang-Nail Current	
Slash Pine	MGP15	25	736	166	145	143	115	JD5
~~Radiata Pine~~	~~F11~~	~~20~~	~~588~~	~~154~~	~~134~~	~~136~~	~~130~~	~~JD4~~
Victorian Ash	F17	20	652	157	160	134	180	JD3
Hoop Pine	Clear	22	501	170	145	152	115	JD5
Hoop Pine	Pith-in	20	474	135	126	113	115	JD5

A similar analysis for the perpendicular-to-grain results shows that the mean density of a product can be used to estimate tooth design strengths.

Species like Slash Pine with relatively large density differences across 5 or so grades, are likely to have steeper design curves than species like Australian eucalypts which have a minimal density difference between grades. Apart from overall wood density, some species are also likely to have different design values due to density variations within the timber. eg. species with pronounced earlywood latewood bands may have lower resistance to load due to low perpendicular-to-grain strength. For these reasons it would seem unlikely that an efficient design curve to cover all species could be developed. Figure 2 shows the relative nature of design strength - density design models for different timber types. This figure is intended to simply show the possible relative nature of design curves and how they may vary depending on the density characteristics of different timber groups. Tooth strengths have deliberately not been assigned to the Y-axis and should not be assigned in any way from this figure.

Figure 2. Relative Tooth Strength Design Models for Different Timber Types



CONCLUSIONS

1 . Species based systems for assigning tooth design loads for different grades of Slash Pine can be overly conservative for the higher grades and unconservative for the lower grades.

2 . The design strength of toothed metal plate connectors is sufficiently proportional to the mean density of Slash Pine products to allow mean product density to be used to determine tooth design strengths.

3 . Determining design strengths for different grades of slash pine using mean product density will result in more cost efficient and reliable timber structures.

4 . The proposed CSIRO "Greybox" method of determining design strengths for connectors, will result in about a 12% lowering in design strengths for toothed metal nail plates, if adopted in its current form.

RECOMMENDATIONS

1 . Providers of engineering design information for toothed metal nail plate design should consider adopting grade based design strengths for Slash Pine.

2 . The tooth strength, density and grade relationship of other commercial timbers should be investigated, with a view towards a more efficient grade based tooth design strength system.

3 . CSIRO should further review the calibration of the proposed "greybox" method.

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STRUCTURAL BEAMS AND DEEP JOISTS - A Comparative Review

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Abstract

For a number of decades now, builders have been restricted in their use of long spanning members through cost and availability of materials. Builders are also slow to change and have conservative habits . However, in recent times there have been limited options or choice being restricted to F7 oregon and F17 hardwood. Manufactured long spanning members now provide a real economic and structural alternatives for use as floor joists and rafters. This paper examines and compares the "traditional" timbers with the new "manufactured members".

Introduction

The building industry is very conservative by nature and slow to adopt changes. People involved in marketing within the industry know well the difficulty in having new products accepted. Usually it requires something extraordinary, either a highly imaginative and economical product or substantial cost increases to existing elements rendering total building costs prohibitive. Examples of this are the advent of Tilt Up Concrete construction to supplant brickwork which became so expensive. A more recent example is the doubling in price of imported F7 oregon leading to the acceptance of trussed floor joists and continuous plywood laminated structural elements

The opportunity arose for the comparative study when a client requested the second phase of his house construction; the addition of two bedrooms and a garage.

The garage presented the challenge because the brief stipulated a clear flat plasterboard lined ceiling was essential. The client wanted the garage to open up so that the space could be used in association with outdoor entertaining. Refer to Diagram 1, next page.

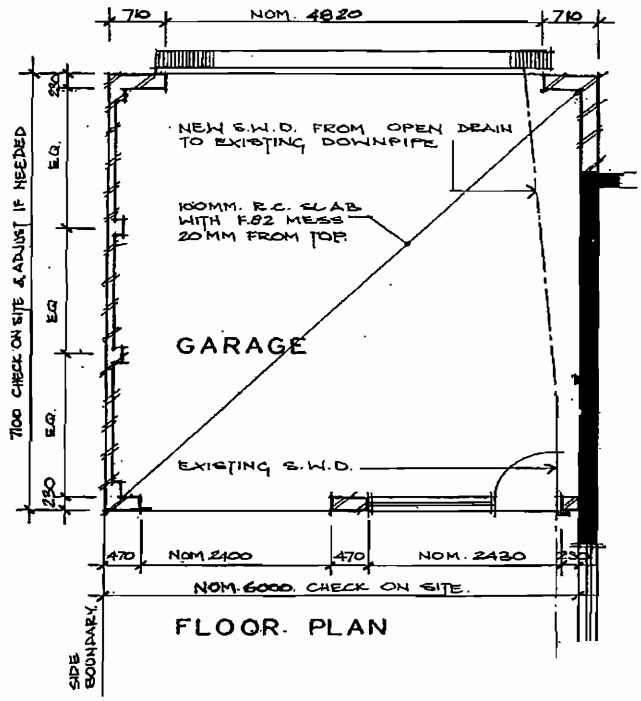

DIAGRAM 1 : Garage Plan

Use of plasterboard necessitated the roof beam spacing be fixed at 600 centres.

Regardless of which roof beams are selected, 100 x 75 F8 HW top plates anchored to the walls and piers would need to be used. The comparison is based upon the cost of the roof beams only and associated labour. The project will require twelve roof beams at 600 cc to service the 7.1 m length of the garage. Refer to Diagram 2.

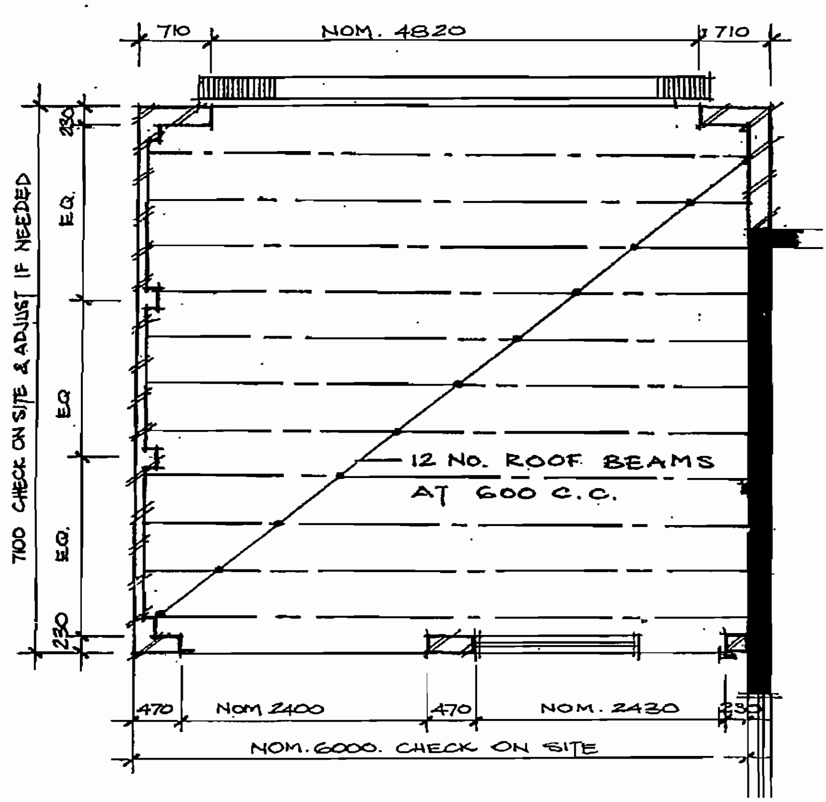

DIAGRAM 2 Plan of Rafter Layout

A comparison of the following alternative beams and joists were made:

- Hyspan Laminated Veneer Lumber
- Posi-Strut Flat Chord Trusses
- F7 Oregon
- Seasoned Hardwood.

HYSPAN, LAMINATED VENEER LUMBER (LVL)

This is a continuous timber veneer laminated structural material. It is manufactured from dried rotary peeled Pinus Radiata Veneers laminated together under beat and pressure. The grain direction of all the veneers is oriented in the long direction of the beam, that is, the direction of the span. These plywood laminated beams have now gained acceptance by both, builders and carpenters. They have proved themselves by substantiating the manufacturer's claims.

Timberbuilt's Technical Bulletin No. 1 states:

"The effect of laminating in excess of 10 veneers not only increases strength by the removal of the weakest link: but also significantly enhances reliability, uniformity and predicability A predictable material can be used with a greater sense of confidence and it is this important property that makes Hyspan LVL a sought after engineering material for critical, primary beam sand structures."

Stability is an important consideration for builders. If they can rely on a member not to warp, bow or twist it then becomes a straightforward financial consideration. Often the builder is prepared to pay a little more for peace of mind.
Carpenters do appreciate the uniform straightness of the material and easy handling due to its light weight compared to the solid sawn timbers. From the manufacturer's Technical Bulletin No. 1 table 11, refer to diagram 2, we determine we need to use 240 x 45 members at 600 centres.

The cost estimate is as follows:-

			$
Material Cost:	12 No. @ 6.0m = 72m @ $12.30 per m.	=	885.60
Labour	subcontract carpenter quote	=	200.00
	Hyspan LVL: Total		$1085.60

POSI-STRUT FLAT CHORD TRUSSES

Posi-strut trusses are parallel chord trusses using softwood chords "of flat" with cold rolled galvanised steel "V" webs. The profile is similar to the fabricated steel open web joists. Trusses have fixing point flexibility and may be supported on the bottom chord by resting on a plate or top chord supported. However if top chord support truss is chosen the top chord needs to be reinforced as directed by the manufacturer.

Three main advantages of this structural element are:-

1. Greater spans can be achieved with Posi-strut Trusses than with solid timber members making them ideal for creating large open areas.

2. Shrinkage problems are reduced or eliminated.

3. They are lightweight and easy to handle.

Depth of trusses ranges from 197 mm to 412 mm and stress grading F5, F8, F11 (softwoods) and F17. For this comparative study, using the Gang-Nail Rafter and Purlin Design Instructions, and using table 2 we establish, for our needs we can use a PS20, F8 truss. That is, overall depth of 197 mm using 90 x 45 chords at 600 centres.

The cost estimate is as follows:-

			$
Material Cost:	12 No. @ 6.0m = 72m @ $9.80 per m	=	705.60
Additional stiffening	4 No. @ 3.6m = 14.4m @ $2.60	=	37.40
Labour	Sub Contract Carpenter Quote		200.00
	Posi Strut: Total		$943.00

F7 OREGON

Imported oregon has enjoyed wide acceptance by builders. However, price fluctuations and availability on demand has dented the confidence of builders.

Properties of oregon are well known, consequently it is not proposed to discuss them in this paper.

From the Timber Framing Manual we establish we need to use 300 x 75 members at 600 centres.

The cost estimate is as follows:-

			$
Material Cost:	12 No. @ 6.0m = 72m @ $13.75 per m	=	990.00
Labour	Sub Contract Quote	=	250.00
Extra brickwork required due to depth of members			
	4 No. @ 3.6m = 14.4m @ $2.60		235.20
	F7 Oregon: Total		$1475.00

SEASONED HARDWOOD (F17)

As with oregon, the properties, advantages and disadvantages are known and will not be covered here.

From Timber Framing Manual we establish we will need 245 x 45 members at 600 centres.

The cost estimate is as follows:-

			$
Material Cost:	12 No. @ 6.0m = 72m @ $15.68 per m	=	1128.96
Labour	Sub Contract Carpenter Quote	=	225.00
	Seasoned Hardwood: Total		$1353.96

COMPARISONS

The cost results are summarised in the Table below:-

TABLE 1 COST COMPARISON

System	Cost			
	Material $	Labour $	Total $	Index
L.V.L. Hybeam	885.60	200.00	1085.60	115
Posi-Struts	743.00	200.00	943.00	100
Oregon	1225.20	250.00	1475.20	156
Seasoned HW	1128.96	225.00	1353.96	144

WEIGHT COMPARISON

The weights of the various alternatives are given below:

Table 1 Comparative Weights

System	Weight/LM	Weight per Member
LCL Hybeam 240 x 45	6.90 kgm	41.40 kgm
Posi Strut ps 20	6.00 kgm	36.00 kgm
Oregon F7 300 x75	14.71 kgm	88.26 kgm
Seasoned F17 Hardwood 245 x 45	7.20 kgm	43.20 kgm

CONCLUSION

Despite the fact that the case study was not based on a complex structure it is evident from the results that manufactured members have become competitive. However it should be stressed all materials can be used in a variety of structures, both as roof members and floor joists. Each project should be assessed on its merit and builders take into account their quality control and calibre of supervisory staff. For example, some builders will use the Hyspan floor joists for a ground floor and Posi-Struts fro floor joists for first floors. This reduces the need for vigilance when installing services. With Hyspan joists care needs to be taken with location and size of penetrations for services, whereas with the Posi-Struts services are fed through the webs. It only needs a simple instruction to tradesmen. "Do not cut the webs." The major disadvantage with the Posi-Struts is that it needs to be treated as a total truss system and has to be priced and used as such. It is not designed to take internal load bearing walls.

It is clear from the above simple study that the alternative materials and components have to be seriously considered. On the basis of this comparison it is clear they will be used to an increasing extent.

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MULTI-RESIDENTIAL TIMBER FRAMED CONSTRUCTION (MRTFC)

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ABSTRACT

Multi-Residential Timber Framed Construction (MRTFC) is the term used to describe the use of full timber framing construction systems in multi-residential developments. These medium-density developments can take the form of attached dwellings or units on several levels. The basic premise behind MRTFC is the utilisation of fire and sound-rated timber framed wall and floor/ceiling systems to provide for vertical and/or horizontal separation between units/dwellings. These approved timber framed wall and floor/ceiling systems replace other more traditional materials such as concrete, bricks or masonry.

MRTFC is well established in the United States and other developed countries such as Canada, Great Britain, New Zealand and Japan, where it is permissible not only for residential, but also for office buildings, hotels, motels and resorts.

In Australia, timber frame building construction has to date been limited in the main to detached houses (Class 1 buildings). However, the Australian timber industry has been pursuing changes to the Building Code of Australia (BCA) for some 15 years to permit full timber framed construction in multi unit developments, with approximately $3 million committed to date. Most of this money has been spent over the past five years in carrying out research, completing a testing program for timber framed wall and floor systems and in preparing a strategy for the implementation of MRTFC in Australia. This extensive and unparalleled research has brought about major positive changes to the BCA which now permits full timber framed construction for Class 1, 2 and 3 buildings.

This paper provides background and details of the development of fire and sound rated timber framing systems suitable for use in accordance with the BCA for Multi Residential Construction for Class 1, 2 and 3 buildings.

1. INTRODUCTION

Multi-Residential Timber Framed Construction (MRTFC) has been successfully used in the United States of America for over 40 years, with buildings ranging from two to five storeys in height. More recently other developed countries including Canada, Great Britain, Japan and New Zealand have also adopted MRTFC technology in an endeavour to move towards more cost effective medium density housing. Major Australian cities such as Sydney and Melbourne are also reaching the stage of facing the same population density and consequent infrastructure problems experienced in most large cities in the world.

The demand for accommodation together with the desire to reduce the urban sprawl and associated large infrastructure cost is seeing a great number of multi storey residential buildings being built with an associated call for more affordable housing. This demand for affordable housing can be met with the development and construction of Multi Residential Timber Framed Buildings.

In Australia however, buildings regulations until recently (amendment 7 to the BCA - Nov. 94) restricted the use of full timber framed construction in multi residential developments. The major 'impediments' to the use of timber, under the fire safety requirements of the BCA were the explicit and implicit 'non-combustible' requirements.

For some 15 years, the National Association of Forest Industries (NAFI) and the Australian Timber Industry have been pursuing changes to building regulations, to permit the use of fire and sound-rated timber framed wall and floor/ceiling systems in multi-unit developments. In 1989, NAFI established a fire research office with the specific aim of amending building regulations to allow greater use of performance based, fire and sound rated timber framed construction for Class 1, 2 and 3 buildings.

A $1.5 million Research and Development (R&D) programme was initiated with the principle objective to justify full timber framed construction in multi-unit construction for class 1, 2 and 3 buildings. The R & D programme formed part of a National MRTFC implementation strategy and was seen as the best vehicle to deliver positive Code changes.

2. BUILDING CODE OF AUSTRALIA - BACKGROUND

The BCA is the technical reference document for the design of buildings in Australia. The code is adopted in each State and Territory under separate legislative provisions. Local approval authorities (Councils) or private Building Surveyors are generally responsible for the approval of design documentation. The Code, in most cases, provides a comprehensive suite of provisions which cover the required level of construction for all forms of buildings. In addition, the Code may contain its own specific design criteria or it may adopt an acceptable reference document such as an Australian Standard or other reference which contains criteria to satisfy its provisions.

'The basic objective of the BCA is to ensure that acceptable standards of structural sufficiency, fire safety, health and amenity are maintained for the benefit of the community now and in the future'.

For some time the Code has allowed timber framed construction to be used for residential construction up to two storeys in detached housing (Class 1 buildings), but restricted the use of timber framing in attached multi-unit developments (Class 2 & 3 buildings) . The philosophy behind the Code, appeared to be that in order to achieve BCA objectives, the building should withstand total burnout of all combustible material (including the contents and material of construction) with minimal interference in the process by fire brigade response, or automatic fire detection and/or suppression systems.

It was obvious to the industry that the "non-combustibility" requirements of the BCA presented a major obstacle and disadvantage for the use of timber products in multi-residential buildings as compared with other main material groups eg. Steel, concrete, masonry. NAFI and the Timber Industry realised that to achieve Code changes, regulators had to be provided with evidence of the relative performance of MRTFC systems, to effect their thinking away from a prescriptive "non-combustible" mentality to a more rational performance base. R & D was seen as a powerful tool that could achieve this

3. MRTFC - FIRE RESEARCH OFFICE: R&D PROGRAMME

Historically, Australia has achieved a very high record of fire safety in buildings. This is a reflection of many factors, including building regulations, product design standards and cultural and environmental factors. Building regulations have contributed to the provision of adequate protection over many years, but have impeded the development and use of fire technology in building construction.

NAFI and the Timber Industry watched as various developed countries implemented multi-storey timber frame construction as a move towards more cost effective, medium density housing in recent years and questioned the lack of progress of MRTFC in Australia. While technology in the fire, science and engineering world has progressed greatly in the last decade, little has yet flowed into the building regulations.

One of the major limiting factors that delayed the introduction of MRTFC in Australia was the lack of available resources, both in terms of researchers and funding to carry out the research necessary to demonstrate that this type of construction could meet acceptable standards of structural sufficiency, fire safety, health and amenity.

NAFI and the Australian Timber Industry, after consultation with the Australian Uniform Building Regulation Co-ordinating Council (AUBRCC), decided to undertake the necessary research to investigate MRTFC. Approximately $3 million has been committed to this date with most of this money being spent over the last 5 years in carrying out research and in preparing a strategy for the implementation of MRTFC.

In 1989 NAFI established a Fire Research Office with the long term aim of amending prescriptive building regulations to allow greater use of performance based, fire-rated timber framed construction for Class 1, 2 and 3 buildings.

In order to demonstrate compliance with the intent of the objectives of the BCA, a number of various issues needed to be addressed. Three specific projects were initiated to examine issues revolving around the BCA objectives; **(a) Prototype design, (b) Fire Resistance and Acoustic Testing , (c) Fire Safety Systems Risk Assessment.**

3.1 Prototype Design

The main objective of this study was to demonstrate that timber framed multi-storey housing satisfies Australian community expectations in relation to: fire safety, quality, acoustic separation, design flexibility, cost, the Building Code of Australia A prototype timber frame housing design was adopted for detailed development and investigation. The prototype was chosen carefully to be representative of the public and private sector medium-density housing market.

The design development of the prototype involved the preparation of outline working drawings, with details of construction, that would enable demonstration of the performance of the construction systems with respect to:

- Fire Resistance
- Structural Sufficiency
- Acoustic Sufficiency
- Construction Program
- Construction Costs
- Risk Assessment details

Six models (differing construction systems) were developed to compare various cladding, fire resistance, acoustic performance and construction detailing. The various models were based on the same building envelope, standard of finishes, site planning and level of servicing. One model was the BCA - complying traditional masonry loadbearing construction for comparison purposes and the other five models were all of timber frame construction.

The individual models were assessed as follows:

- Fire Resistance Rating and Acoustic sufficiency were determined by laboratory testing of assemblies based on the model details. See Section 3.2.
- Structural sufficiency, construction programme and construction costs have been based on specialist consultants' advice.
- Risk-Cost Assessment was done by computer models that were developed for the purpose of evaluating risk to life and fire resistant construction costs. See Section 3.3.

From the findings of the prototype tests, it was concluded that the structural sufficiency, health and amenity requirements of the BCA can be met by 3 storey timber frame construction. Furthermore, the project demonstrated that this type of construction can provide the community with not only more affordable accommodation, but also provide more variety, flexibility and individuality in design and so better quality of life.

3.2 Fire/Sound Testing

Fire Testing

In order to demonstrate performance levels of lightweight timber frame systems, NAFI engaged the services of CSIRO to conduct fire tests of a number of timber wall and floor/ceiling systems. A programme of testing various timber frame assemblies (based on the prototype model designs) to AS1530.4 'Fire Resistance Tests of Elements of Building Construction' was undertaken by CSIRO (DBCE - Fire Technology Group). These tests were carried out with loadings applied that were in excess of those needed to satisfy the BCA for structural sufficiency for the 3 storey prototype building. This testing has demonstrated, through the severe furnace testing to AS1530.4, the effectiveness of this type of construction in resisting the spread of fire and smoke. It has also demonstrated the Fire Resistance Levels (FRL's) of various timber wall and floor/ceiling systems. (Se tables 1, 4 and 5).

AN OVERVIEW OF THE FWPRDC PROJECT - BREEDING OBJECTIVES AND TREE SELECTION CRITERIA TO MAXIMISE THE VALUE OF SAWN TIMBER

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ABSTRACT

The increasingly commercial approach to softwood plantation management is encouraging growers and processors to collaborate to ensure the value of products recovered from the future resource is maximised. This project is aimed at establishing economic based breeding objectives and plus tree selection criteria. This three year project will be undertaken in three stages, which are:

i) Detailed assessment of tree and wood quality traits, followed by processing and value model development.
ii) Calibration of the predicting value from tree and wood characteristics.
iii) Establishment of plus tree selection criteria for achieving breeding objectives.

Early analysis of the data presented here is encouraging and suggests project objectives will be achieved. The successful completion of the project is expected to bring many benefits to Australian softwood growers and processors.

INTRODUCTION

Background

Public forest growers are becoming increasingly commercial in their development of plantation management policy. As a result, their focus is turning toward maximising the return on investment for their shareholders. In addition to reducing production costs and increasing production, the improvement of standing tree quality is also being pursued. In the past, selection decisions regarding the genetic character of planting stock have been based largely on traditional objectives *e.g.* size, straightness, taper, branching characteristics and wood density. The development of improved planting stock has realised significant advancements in recent years, however there is a need to quantify the impact of the various tree and wood quality parameters on subsequent value of wood products that can be recovered from a tree.

In Queensland, the public forest grower, DPI Forestry, through their tree breeding and wood products research programs at the Queensland Forestry Research Institute (QFRI), have sought information from customers (softwood sawmillers) about what would be the desirable characteristics of the future softwood resource. Consultation has been undertaken through field days which examined trials representing progressive improvements achieved by the tree breeding program, new directions in clonal forestry and research into relationships between wood product quality and tree characteristics. The project described in this paper has been initiated as a result of these consultations, and reflects a growing co-operation between forest grower and processor that will undoubtably lead to better forest management policy and higher quality wood production. The purpose of the paper is to present the objectives, strategy and early results of the project.

The project participants include Hyne and Son, The Forest and Wood Products Research and Development Corporation, The Australian National University, the CRC for Temperate Hardwood Research and the Qld Forestry Research Institute.

Project Objectives

The objectives of the project can be summarised as follows:

- To develop breeding objectives which will maximise profit from sawn timber production
- To define early selection criteria to realise these breeding objectives
- To develop a predictive model for industry to estimate sawn recovery and product value from standing trees.

Project Strategy

The strategy for achieving the above objectives is as follows:

- Define a production system for sawn timber and associated products, from establishment to market, and determine the associated sources of incomes and costs
- Determine biological traits which influence income and costs, and assess each in a sample of mature trees of a range of genotypes
- Estimate economic importance and genetic parameters of each important biological trait, and define breeding objectives
- Construct and compare selection indices. Verify indices using a separate sample
- Develop and verify a predictive value model for use by industry.

The project is comprised of three stages:

- Stage 1 - Undertake detailed tree and wood quality assessments of a selection of stems. Process these stems according to a defined production system and gather a detailed set of value data. Develop relationships between tree and wood characteristics and finished product value
- Stage 2 - Validate the relationships developed in stage 1 by processing a large sample in a commercial sawmill
- Stage 3 - Estimate the genetic control of important traits identified in stages 1 and 2. Determine the most appropriate plus tree selection criteria and assign true economic weights to selection indices.

Both slash pine ((*Pinus elliottii* Engelm. var. *elliottii* L. & D.) and Honduran Caribbean pine (*Pinus caribaea* Morelet var. *hondurensis* Barrett & Golfari) will be studied in the context of structural products recovery, and Caribbean pine will be studied as a source of appearance grade products. In each product by species class, six sites by 25 trees (150 trees) will be studied in stage 1.

EXPERIMENTAL METHODS

The experimental method for the project was designed to identify relationships between tree and wood quality parameters, and finished product value.

Tree Selection

Sites were selected from plantations established between 1968 and 1975 using stock raised from seed collected in the Landsborough or Nursery clonal seed orchards.

Sites were selected at Beerburrum, Toolara and Tuan State Forests to yield trees aged between 22 and 28 years, average diameter between 32 cm and 38 cm, with at least 70% of stems greater than 23 cm DBHOB. At each site a distribution of diameter was established from a large sample (400+ trees), and subsequent tree selection was directed toward representing this diameter distribution within the final selection of 25 trees taken for study.

Field Measurements

The field assessment methods were developed by QFRI staff in consultation with resource assessment staff of Hyne and Son Ltd. It was envisaged that this collaboration would lead to relevant and useful assessment procedures. The following parameters were assessed:

- Size - DBHOB
- Height - total tree height while standing, and measured to a 15cm diameter top (sawlogs) and a 6cm top (pulpwood) after falling
- Straightness - a subjective assessment based on a 20 point scale of criteria (0 = poor, 20 = good) developed by QFRI staff in consultation with Hyne and Son resource managers to predict the length of merchantable, straight logs in the first 12m section - and a conventional 6 point assessment used in tree breeding assessments
- Branch characteristics - mean and maximum size, number and internode distances estimated in the standing tree or measured after falling. Measurements were taken from the lower third of the green crown only so as to be representative of the merchantable part of the tree
- Bark thickness measured with a bark thickness gauge
- Stem lean - estimated
- Crown defects - presence and number of ramicorns and basket whorls.

Wood Quality Lab Measurements

Wood sample cores were taken from each sample tree at breast height, and these were processed in the laboratory to yield the following:

- Basic density measured by gravimetric methods in 5 ring segments from pith to bark
- Spiral grain measured at each ring for rings 1 to 12 and at rings 15, 20 and 25
- Diameter under bark at age 5, 10, 15, 20 and 25 years. These values are used to calculate basal area at these ages.

Pre-Processing Measurements

After harvest each selected tree was cut to length for haulage and transported to the Hyne and Son sawmill at Tuan, where each stem was further merchandised according to standard criteria employed at that mill. Sawlogs were transported to the QFRI Salisbury research sawmill, and measured for the following before sawing:

- Small and large end diameter under bark on two principle axes to the nearest centimetre
- Sawlog length to the nearest 10 cm
- Log sweep measured as deviation from a string line at 1,2 or 3 positions as necessary.

Processing Strategy

The processing strategy for either structural product recovery or appearance grade recovery was designed to mimic the Hyne and Son Tuan sawmill process and sawing patterns, but undertaken at the QFRI Salisbury research sawmill.

Product Evaluation

Evaluation of finished product was designed to mimic the standards applied by Hyne and Son Ltd. Data was gathered for the following parameters:

- Green sawn recovery of both sawn structural and board products
- In-grade or out-grade based on visual grading of distortion, knots, incidence of resinosis (particularly resin shakes) and other features as defined by the Hyne and Son process
- Values for MOE and F grade from machine stress grading.

PRELIMINARY RESULTS AND DISCUSSION

The project has three stages, and the first report from the project is due in February 1997. It will provide results of statistical analysis of data for 150 slash pine trees cut to structural product. At the time of preparing this paper, data for 100 of these slash pine trees only were available for analysis and presentation, however these are adequate to illustrate the strategies of the project. Three trees were removed from the data set as outlines leaving a total of 97 trees.

Any biological system is maintained through a complex interaction of environmental factors and genetics. Statistical analysis of these interactions can feature large error terms because interactions are complex and may vary over the range of values for any given parameter. This especially is the case when dealing with a large number of environmental parameters, in the context of a poor knowledge of the interactions. The outcome of statistical analysis which is guided in part by the available knowledge of forest science, must be considered carefully when drawing conclusion from the data. The second stage of the project, which involves validation of the models through processing and evaluation of a very large sample, will be critical to establishing the credibility of the outcomes of the project.

The dependant variable in this analysis is value or “dollars”. For the purpose of this paper, this has been expressed and discussed in two forms. Firstly, the gross value of a tree in dollars, which is calculated as the sum of the value (based on grade and volume) of each stick of framing timber cut from a tree. The values assigned for each grade were estimates of the market values for June 1996. Secondly, the "intrinsic" value of the wood which is calculated as gross value of the framing timber cut from a tree divided by the total volume of these sticks. This gives a value as dollars per cubic metre of sawn framing timber. Note that references to product value and volume relate to framing timber only. The independent variables that have been chosen for presentation are listed in the methods section.

The Range of Parameter Values Captured in the 97 Study Trees

Before a consideration of the results can be undertaken, it is useful to initially review the range of parameter values that have been captured in the 97 study trees. For the purpose of displaying the range of data values, the following sections refer to distribution histograms for each parameter measured.

Stand Information

It was considered that the stands selected for study should include trees exhibiting a range of parameter values typical of the slash pine resource grown from orchard grade seed. This wood will begin to be cut commercially in the near future. Selected descriptive stand information is presented in Table 1.

Table 1: Stand descriptive information - slash pine

Site Number	Tree Numbers	Cpt Nbr	Logging Area	District	Age	Current Stocking (spha)	Thinning History
1	01-25	25	Coochin	Beerburrum	26	590	T1
2	26-50	93	East	Tuan	26	383	T1
3	51-75	18A	Coochin	Beerburrum	26	610	T1
4	75-97	20	Magnolia	Tuan	28	467	T1

Tree Sawlog Volume

Figure 1 shows the distribution of log size classes in the 97 trees study sample. Based on typical sawlog volume currently supplied to Queensland sawmills (unimproved genetic material), the sample set is on average a little larger than current log intake.

Note that tree sawlog volume implies the sum of individual sawlog volumes recovered from each tree. Due to variation in allowable load lengths for transport, the top diameter limit for sawlog varied slightly between sites at Beerburrum and Tuan, and provides a source of error when comparing to commercial sawlog volume data.

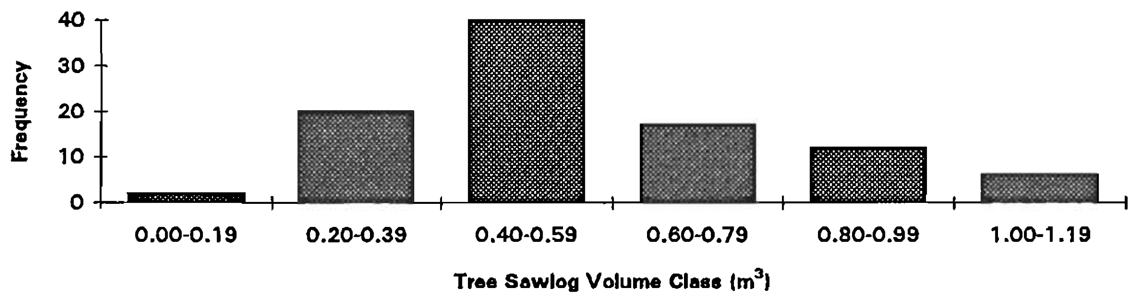

Figure 1: Distribution of tree sawlog volume for 97 study trees

Wood Density and 10-year-old DBHUB

Figures 2 and 3 show the range in wood density and 10-year-old basal area for the sample set. The latter parameter is used as an indicator of juvenile wood volume. The location of the juvenile/mature wood boundary is transitional and difficult to establish. The assumption that the volume at age 10 represents juvenile wood, is based on standard approximation from the QFRI research database.

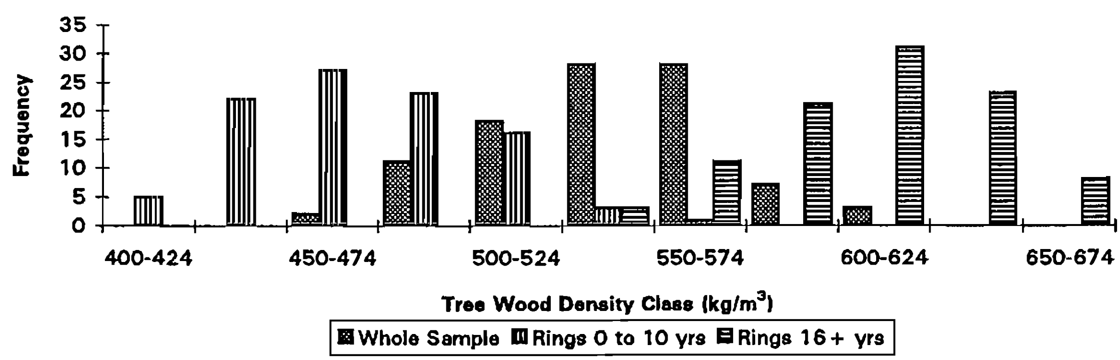

Figure 2: Distribution of density for 97 study trees

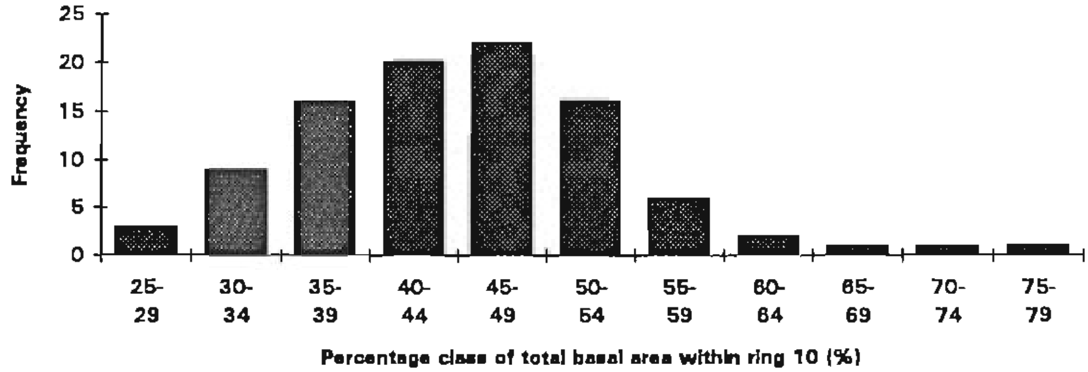

Figure 3: Distribution of 10-year-old basal area for 97 study trees

Straightness

The straightness assessment method used in this analysis was based on a 1 to 20 point scoring system developed for the project. Figure 4 illustrates the full range of values that have been represented in the sample set.

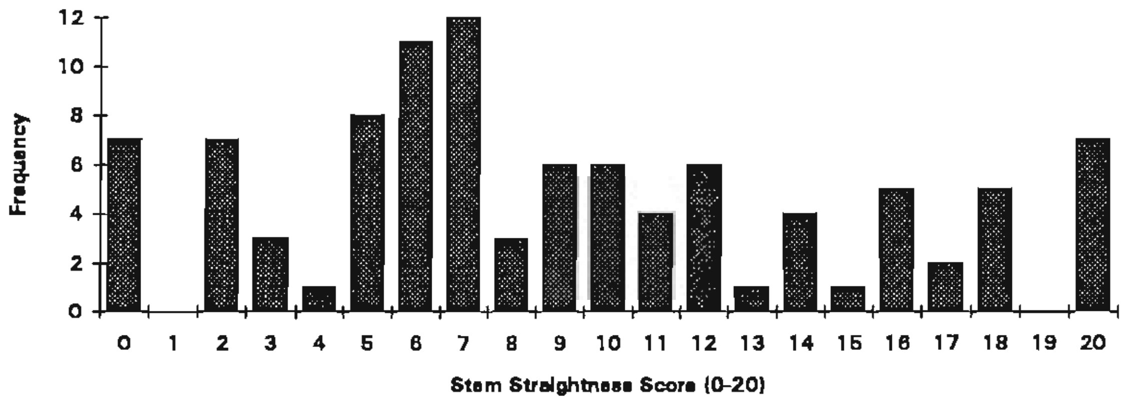

Figure 4: Distribution of straightness scores for 97 study trees

Branch Characteristics

Figures 5 and 6 illustrate the range in branch size, and number of branches for each tree in the study sample. Note that these values were determined from the lower third of the green crown.

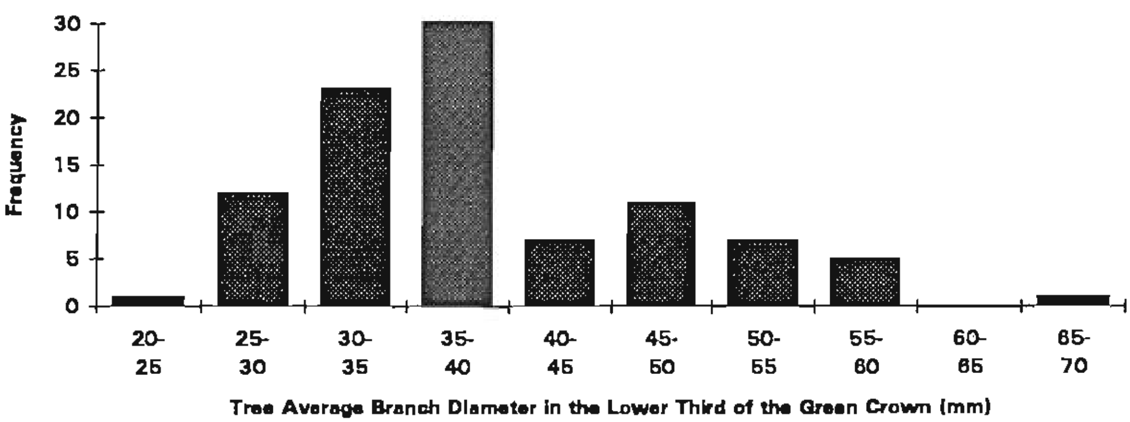

Figure 5: Distribution of branch size for 97 study trees

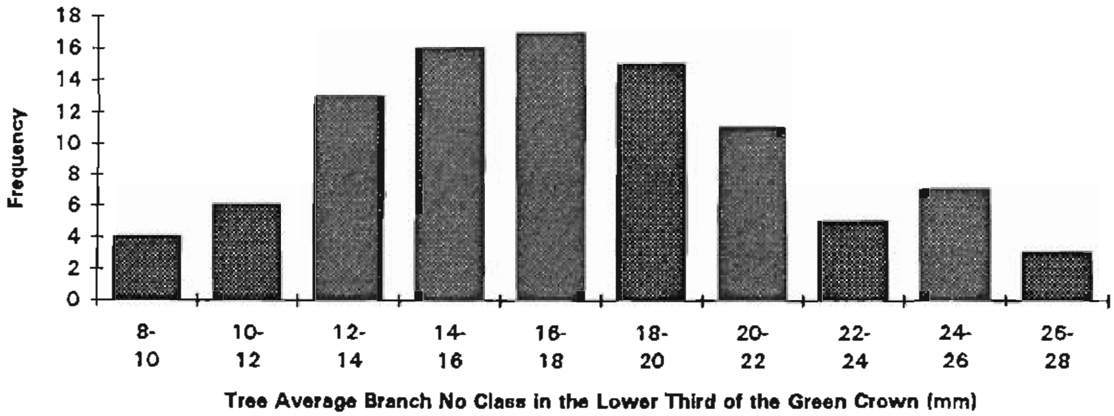

Figure 6: Distribution of number of branches for 97 study trees

The Effect of Volume on Value

Intuitively, tree volume is expected to heavily influence the gross value of sawn material recovered from any tree. Figure 7 illustrates this expectation, and as shown in Table 2, the relationship between value and volume is good, indicated by the small error sum of squares of the regression model. Note that the volume is for framing sizes only.

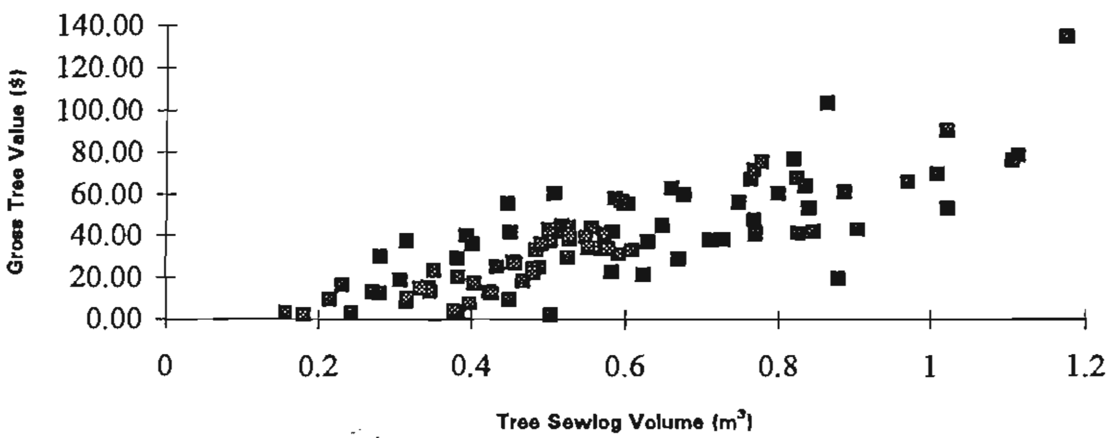

Figure 7: Tree sawlog volume versus gross value of recovered framing

Table 2: Regression summary - Tree sawlog volume versus gross value of recovered framing

Dependent Variable: Gross Value ($'s)

Source	DF	Mean Square	F Value	Prob > F
Model	1	34566.26	167.628	0.0001
Error	95	206.27		

R^2 = 0.638 C.V. = 37.43

In the context of the influence of volume on gross value, it is difficult to imagine other tree and wood quality parameters having comparable impacts. Despite this and as will be shown, these other parameters do effect gross and intrinsic value of sawn timber, and therefore are relevant to optimisation of forest product quality.

The effect of volume on the intrinsic value of sawn material or value per cubic metre of framing recovered is shown in Figure 8.

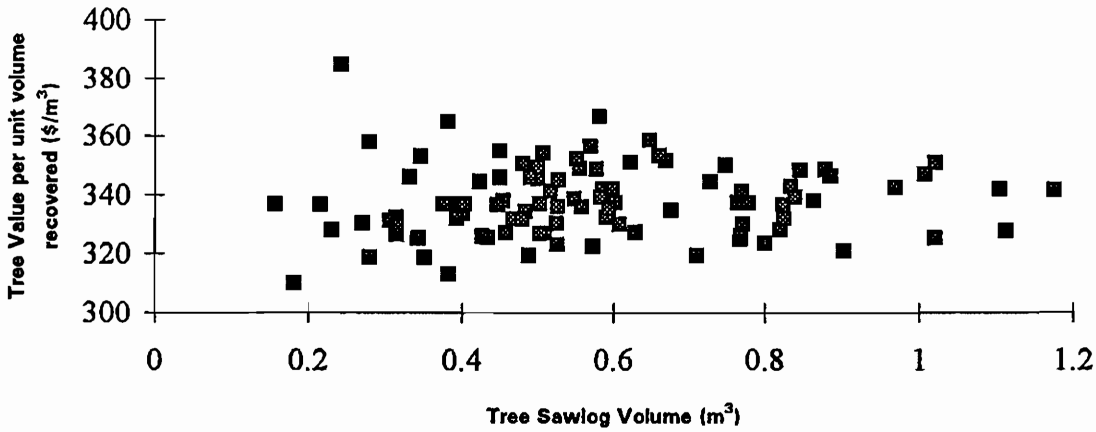

Figure 8: Tree sawlog volume versus value of framing per cubic metre of framing recovered

Figure 8 illustrates independence of intrinsic wood value and tree volume, which implies that big trees do not necessarily represent trees with poor intrinsic wood value.

The Effect of Straightness on Value

Anecdotal evidence from softwood sawmillers, suggests the straightness of a log has significant implications for both handling, processing, recovery and therefore value. Figure 9 shows the relationship between gross value of framing recovered from each tree in the study sample and straightness score.

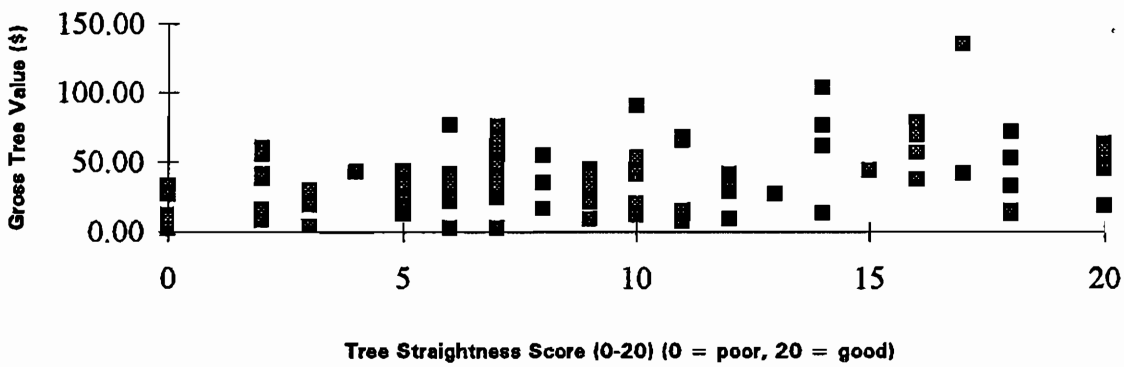

Figure 9: Tree straightness score versus gross value of recovered framing

Table 3: Regression summary - Tree straightness score (1- 20 scale) versus gross value of recovered framing

Dependent Variable: Gross Value ($'s)

Source	DF	Mean Square	F Value	Prob > F
Model	1	7722.25	15.793	0.0001
Error	95	488.96		

$R^2 = 0.142$ C.V. = 57.63

Note that the analysis does not include boards that were cut from the perimeter of the log during sawing, and therefore the sensitivity in terms of recovery has not been shown completely. However, a relationship between gross value and straightness is implied in Figure 9, although Table 3 indicates the direct relationship is not strong.

Figure 10 shows the relationship between straightness score and the value of framing per cubic metre of framing recovered.

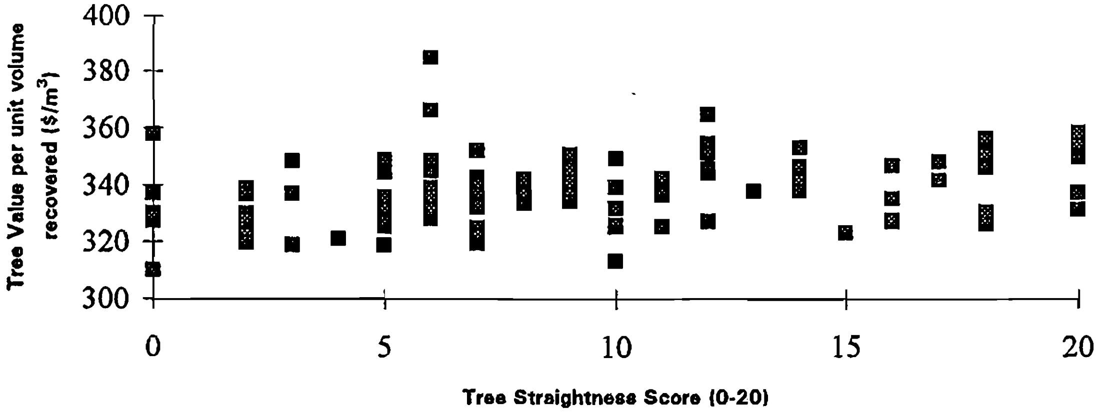

Figure 10 : Relationship between straightness score and the value of framing per cubic metre of framing recovered ('intrinsic' value).

Table 4: Regression summary - Tree straightness score (1 to 20 scale) versus value of framing per cubic metre of framing recovered.

Dependent Variable: Intrinsic Value ($/m³)

Source	DF	Mean Square	F Value	Prob > F
Model	1	1204.616	8.657	0.0041
Error	95	139.151		

$R^2 = 0.084$

In addition to the effect on gross value, there is an indication of effect on the intrinsic value of wood. The mechanism of this effect is potentially related to the influence of tree straightness on grain orientation within a sawn board, and the resulting distortion that can occur during drying when grain orientation is sloping relative to the board axis.

The Effect of Wood Density

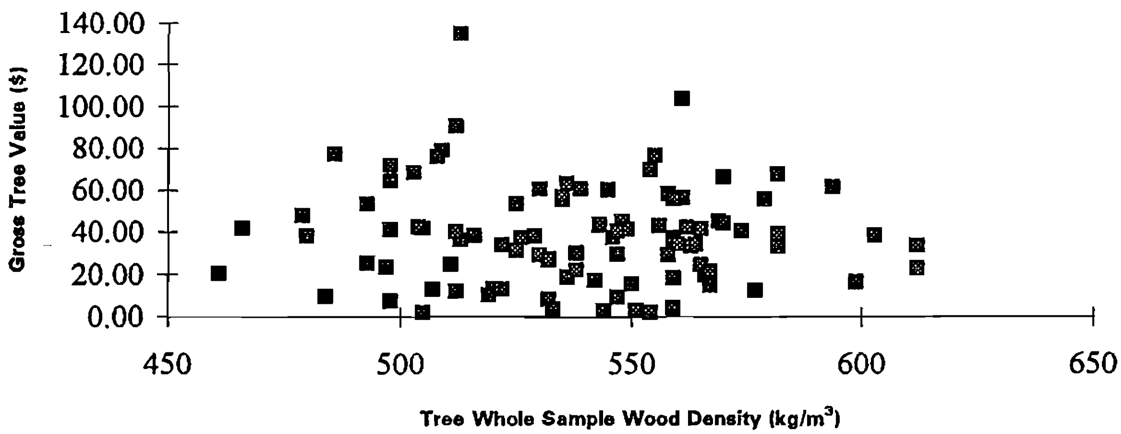

Figure 11: Tree wood density versus gross value of recovered framing

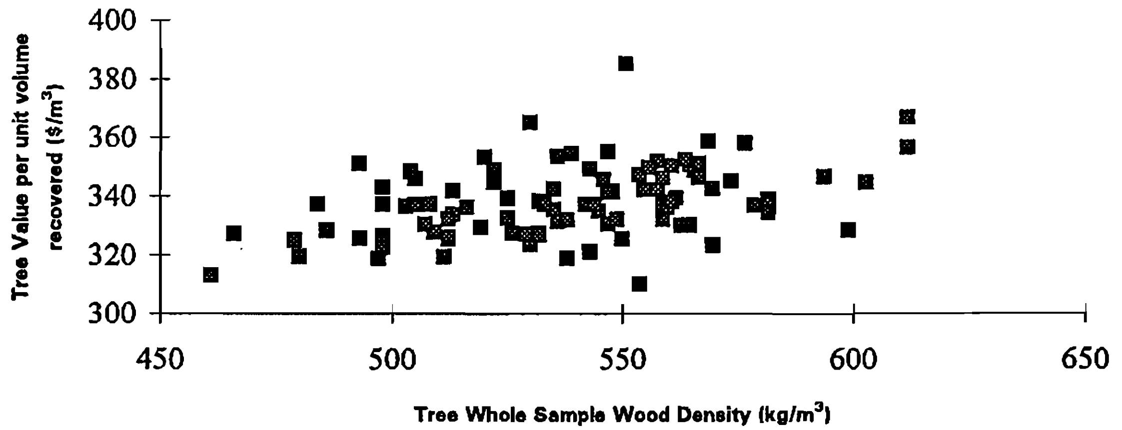

Figure 12: Tree wood density versus value of recovered framing per cubic metre recovered

Table 5: Regression summary - Average wood density (extracted weighted breast height basic density) versus value of framing per cubic metre of framing recovered

Dependent Variable: Intrinsic Value ($/m³)

Source	DF	Mean Square	F Value	Prob > F
Model	1	2374.46345	18.721	0.0001
Error	95	126.83716		

$R^2 = 0.165$

The density of wood in a tree has an effect on the intrinsic value of framing, with value rising with density. Of course, the valuation algorithm places higher value on material graded to F8 and F11 over material graded F5. The density effect on strength has been well documented (Bootle 1985, Haygreen and Bowyer 1982), and the mechanism is illustrated again in the data presented here in Figures 11 and 12 and Table 5.

The Effect of 10-year-old basal area (juvenile wood volume)

The juvenile wood volume in any tree is expected to vary with tree size if free growth has been achieved during the life of a tree. That is, the percentage of juvenile wood (defined here as the basal area that is included in the first 10 rings), should be approximately constant across the range of tree sawlog volume. This relationship is shown in Figure 13.

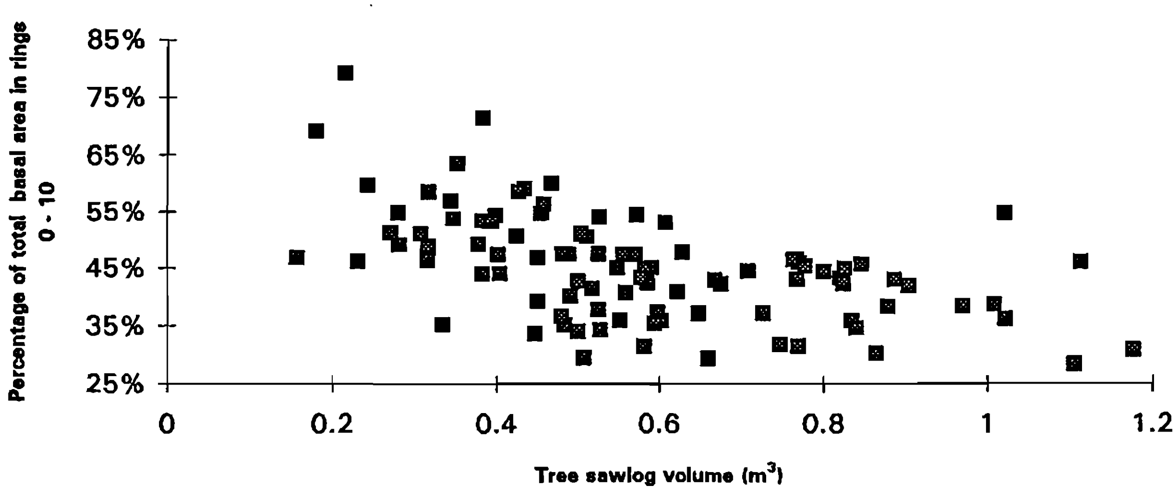

Figure 13: Tree sawlog volume versus the percentage of basal area in 0 to 10 rings

The figure shows, that an approximately constant percentage of juvenile basal area is achieved for tree sawlog volumes above approximately 0.6 m³. Below this value, the percentage of basal area in rings 0 to 10 steadily increases with reducing sawlog volume. This trend suggests that the trees in the study that have a sawlog volume under 0.6 m^3 have suffered suppression of mature wood growth, and trees providing greater than 0.6 m^3 sawlog volume have maintained good early growth rate in the mature wood. In this context, an examination of the effect of juvenile wood volume on value can be undertaken.

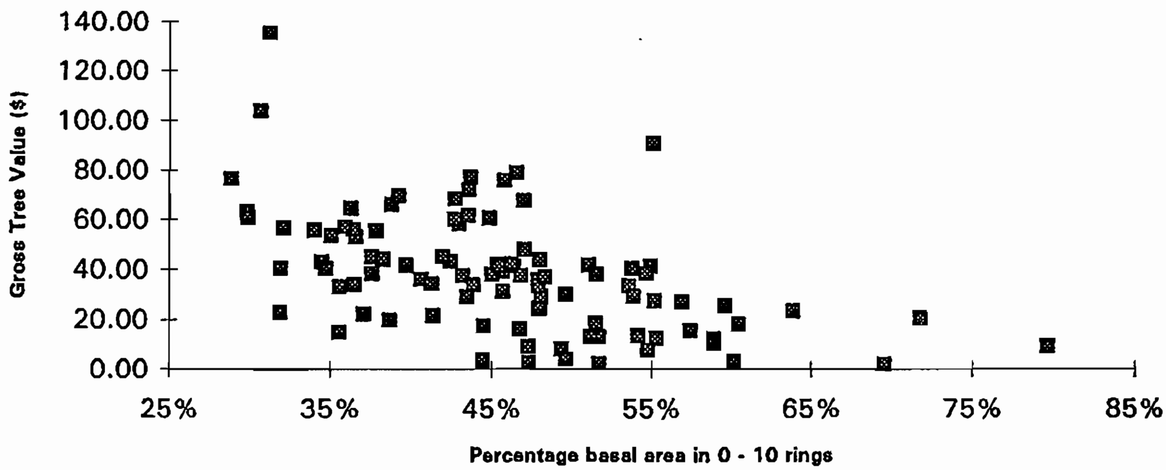

Figure 14: Tree 10-year-old basal area versus gross value of recovered framing

Table 6: Regression summary - Tree 10-year-old basal area percentage versus gross value of recovered framing

Dependent Variable: Gross Value ($'s)

Source	DF	Mean Square	F Value	Prob > F
Model	1	15197.95382	37.044	0.0001
Error	95	410.26620		

$R^2 = 0.280$ C.V. = 52.79

Figure 14 shows an exponential and inverse relationship between gross tree value and the percentage of juvenile wood and indicates the substantially higher value of those trees that have not been suppressed during the mature wood growth phase, and that feature lower proportions of juvenile wood. The linear model described in Table 6 is moderately successful ($r^2 = 0.28$) in fitting these data despite the suggestion of a non-linear component to the relationship.

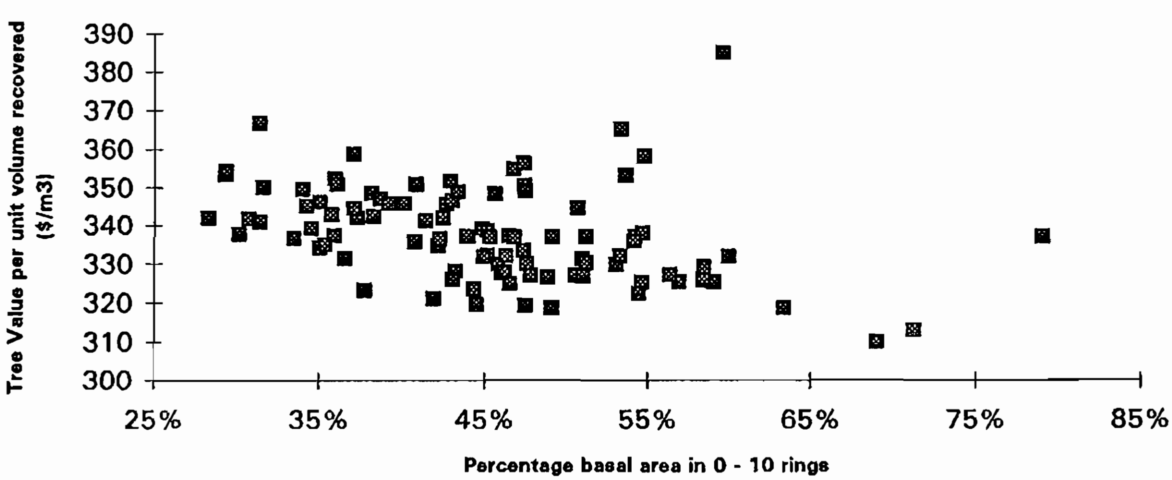

Figure 15: Tree 10-year-old basal area percentage versus value of framing per cubic metre recovered

Table 7: Regression summary - Tree 10-year-old basal area percentage versus value of framing per cubic metre of framing recovered

Dependent Variable: Intrinsic Value ($/m³)

Source	DF	Mean Square	F Value	Prob > F
Model	1	1940.01833	14.763	0.0002
Error	95	131.41026		

$R^2 = 0.134$

Figure 15 shows the relationship between the proportion of juvenile wood in a stem, and the intrinsic value of the framing recovered from a stem. The relationship is linear and therefore, in the context of the discussion above, indicates a real relationship between value of wood in a stem and the proportion of juvenile wood in that stem. The magnitude of the negative slope of the regression line (-0.43), further indicates the level of sensitivity of value to juvenile wood volume.

The corollary to the discussion of the effect of juvenile wood on value, is that silviculture that seeks to promote juvenile wood growth such as direct growth regimes or shorter rotations, is in direct conflict with the objective of improving stem quality and value. The growth of high value wood is clearly a function of mature wood growth, and selection for breeding and plantation management should be directed accordingly. It is acknowledged that this analysis is not exhaustive, and further economic analysis will be required to balance the costs of production against recoverable value. Despite this, it is reasonable to subjectively compare the data in Figure 7 (tree sawlog volume) and Figure 14 (juvenile wood basal area %), and to propose the hypothesis that the effect of proportion of juvenile wood and gross tree volume are likely to produce economic weights of similar magnitude for tree breeding selection indices.

The Effect of Knot Size and the Number of Knots

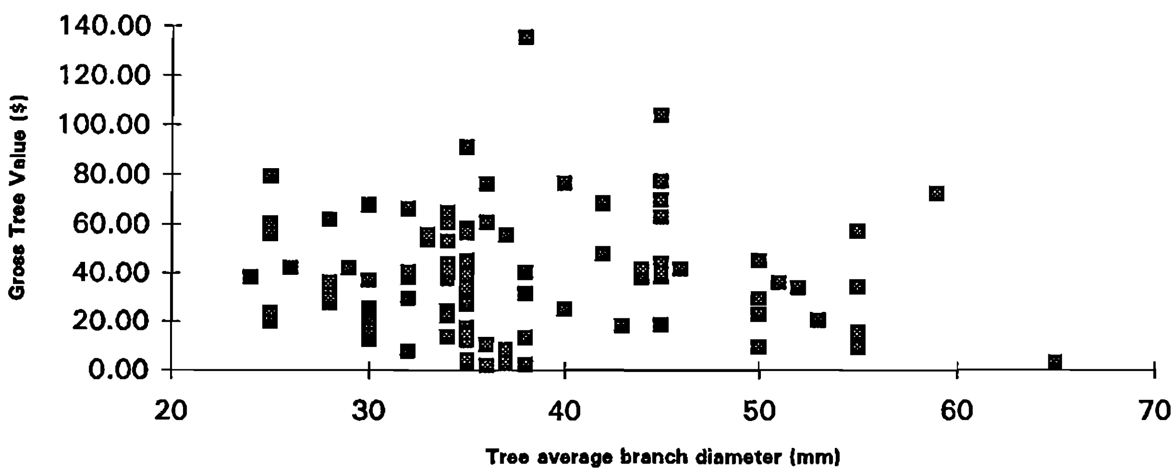

Figure 16: Tree branch mean diameter versus gross value of recovered framing

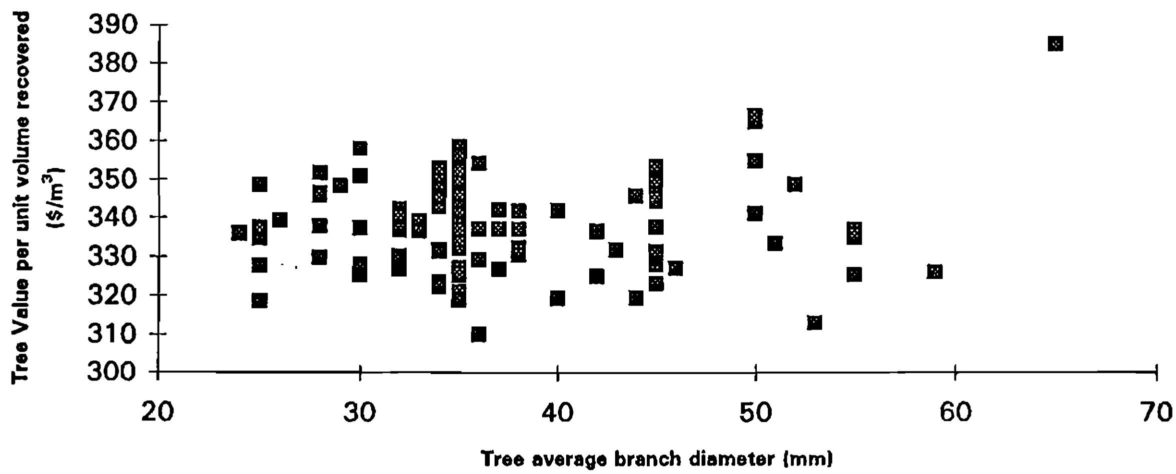

Figure 17: Tree branch mean diameter versus value of framing per cubic metre recovered

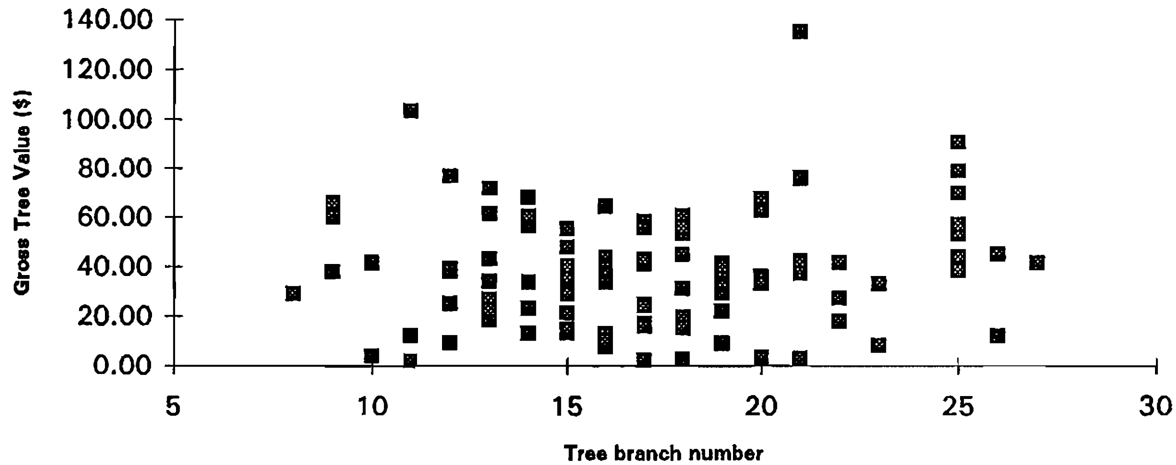

Figure 18: Tree branch number (in the lowest third of the green crown) versus gross value of recovered framing

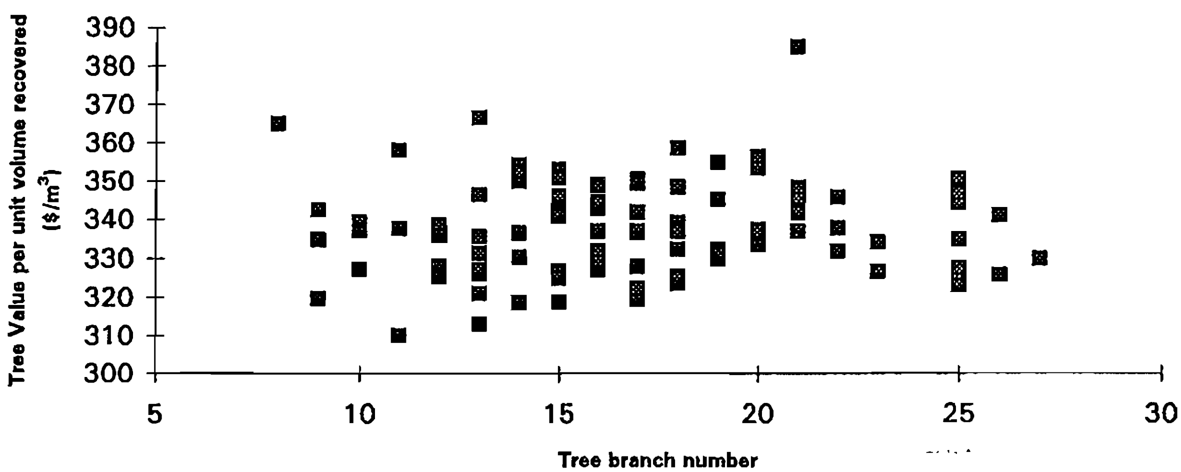

Figure 19: Tree branch number (in lowest third of the green crown) versus value of framing per cubic metre recovered

None of the branch assessment criteria shown in Figures 16, 17, 18 and 19 have been shown to correlate with either gross or intrinsic value.

Toward a Model For Predicting Value

Based on the significance as predictors, the following parameters have been selected to construct a regression model for gross value and value per cubic metre of framing for the study sample of 97 trees:

- For gross value, parameters are:
  - tree sawlog volume,
  - tree straightness, and
  - 10-year-old basal area.
- For intrinsic value, parameters are:
  - tree straightness,
  - wood density, and
  - 10-year-old basal area.

The regression analysis results are summarised in Tables 8 and 9.

Table 8: Regression Summary - Selected tree and wood parameters versus gross value of framing

Dependent Variable: Gross Value of Framing

Source	DF	Mean Square	F Value	Prob > F
Model	3	12131.38002	63.458	0.0001
Error	93	191.17315		

$R^2 = 0.672$

Variable	DF	Parameter Estimate	Standard Error	T for H_0: Parameter = 0	Prob > |T|
Intercept	1	4.629455	11.44470922	0.405	0.6868
Gross Vol.	1	73.989386	7.45574637	9.924	0.0001
Str'ness Score	1	0.567287	0.27116570	2.092	0.0392
10yo BA%	1	-0.307211	0.17936582	-1.713	0.0901

Table 9: Regression Summary - Selected tree and wood parameters versus value of framing per cubic metre of framing recovered

Dependent Variable: Intrinsic Value ($/m³)

Source	DF	Mean Square	F Value	Prob > F
Model	3	1292.20615	11.394	0.0001
Error	93	113.41263		

$R^2 = 0.269$

Variable	DF	Parameter Estimate	Standard Error	T for H_0: Parameter = 0	Prob > |T|
Intercept	1	267.654142	24.12090468	11.096	0.0001
Mean Density	1	0.137086	0.03770397	3.636	0.0005
Str'ness Score	1	0.545221	0.21030045	2.593	0.0111
10yo BA%	1	-0.185035	0.13488149	-1.372	0.1734

The quality of the prediction model for gross value can be illustrated by the following:

- When the data set is ordered by the magnitude of the error, the 5th percentile observation provides a prediction with an error of 49%. The 95th percentile observation provides an error of 1%
- For 5 random samples of 50 trees taken from the full 100 tree data set, the errors in predicted total sample value were 1%, 1%, -11%, 2% and 4%
- For each of the 4 individual sites the errors in predicted total sample value were -7%, 7%, -9% and 20%.

CONCLUDING REMARKS

This paper has been prepared to describe the objectives and methods used in the project, and also to indicate the potential benefit of the work. The quality of the predictive models is encouraging. More detailed analysis leading to better predictive value models, and also to the definition of plus tree selection criteria and weighting, are exciting precedents in the development of plantation and sawmill management methods.

The applicability of the results into the long term future depends heavily on the quality of assumptions that have been made regarding the future utilisation of the resource. Strong arguments have been presented, regarding the relevance of current grading and valuation methods that are used in production sawmills. These discussions, have not resolved this dilemma. However, it is reasonable to propose that the strategy employed is the best available.

The valuation of the wood recovered in the project is based on the approximate value of framing grades in the market at the moment. There are other value parameters that may be considered in this discussion that do not lend themselves readily to quantification. These parameters include the incidence of background resin which leads to difficult handling, or the differential between earlywood and latewood density which leads to difficulty nailing when it is large. These issues have been considered when designing the project. They are included in the data and can be included in the analysis by assuming some range of value adjustments relevant to a qualitative estimate of impact on value. These estimates can then be adjusted to test sensitivity. This process will be undertaken and an assessment of the impacts of these parameters on value will be included when developing selection criteria.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance and commitment of the staff at Hyne and Son Ltd, Tuan Sawmill involved with the project including Dave Bennetts, Rod Grainger, Wayne Schonecht and others, as well as staff of QFRI including Mark Dieters, Paul Toon, Stuart Taylor, Terry Copley, Brian Spillane, Robbie McGavin, Dave Bauer, Brendan Murphy and Toby Djuve. The authors also wish to acknowledge the important involvement of the Forest and Wood Product Research and Development Corporation in co-sponsoring this project.

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A RELIABILITY MODEL FOR DURABILITY

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ABSTRACT

This paper gives a brief description of the concepts involved in the development of a reliability model for use in the FWPRDC project on durability. As an illustration of these concepts, some aspects related to attack by decay are discussed.

1. INTRODUCTION

A key element of the FWPRDC project on durability is a prediction model, i.e. a model that can be used to calculate the risk of failure of a building element to perform satisfactorily due to durability considerations. Ideally we should seek a procedure that can estimate the risk for any element of any type of structure located anywhere in Australia. Such a procedure may be termed an engineering approach and is already available for several alternative building materials.

Prediction models are useful for the development of design procedures and for the optimisation of material selection, maintenance schedules and replacement decisions. Prediction models are essential for the development of performance based standards, the format of future building regulations. They are also essential for the design of innovative systems; by definition this cannot be done solely through experience.

2. PROBABILISTIC MODEL

Figure 1 is a schematic illustration of the key elements of the prediction model. A set of input parameters are used to define the design situation, a particular hazard type is selected, and finally an attack model is used to predict the performance of the element or building system.

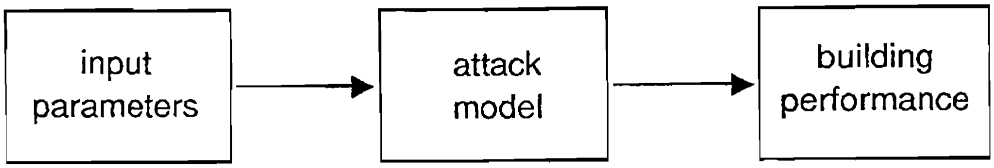

Figure 1. Schematic illustration of the prediction model.

Typical *input parameters* are those that relate to the hazard, building location, building construction, building element and maintenance programs. *Performance criteria* will be classified as either structural collapse, unserviceability (such as excessive deflections, water entry or loss of material) or aesthetic deterioration. Within the scope of the FWPRDC project, the *hazards* investigated will include the following:

- fungi
- bacteria
- termites
- marine borers
- corrosion agents
- climate factors

In the above, the term climate factors is taken to refer to the effects of rain, sun, wind and ultra violet rays on exposed timber. These parameters may lead to surface degrade, aesthetic deterioration, nail popping and extreme distortion of timber elements.

The attack model is assumed to comprise a sequence of events as shown in Figure 2. The duration of each event is a random variable. This leads to a prediction of the statistical time to failure as shown in Figure 3.

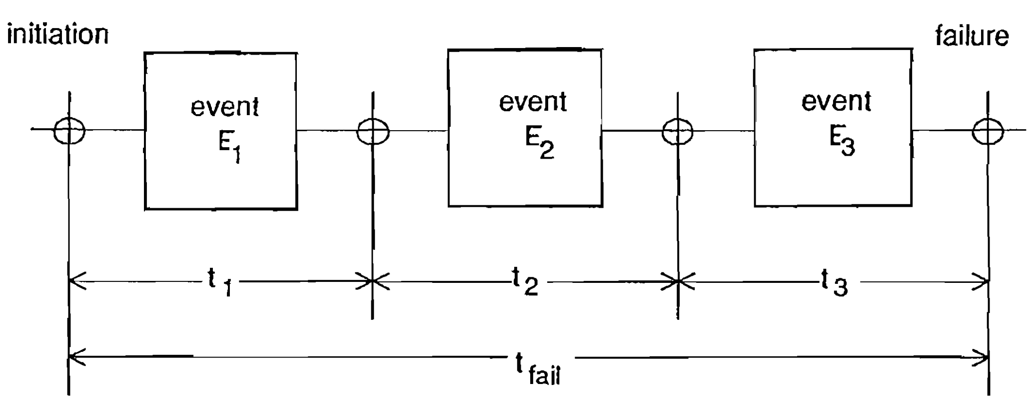

Figure 2. Statistical model of event times.

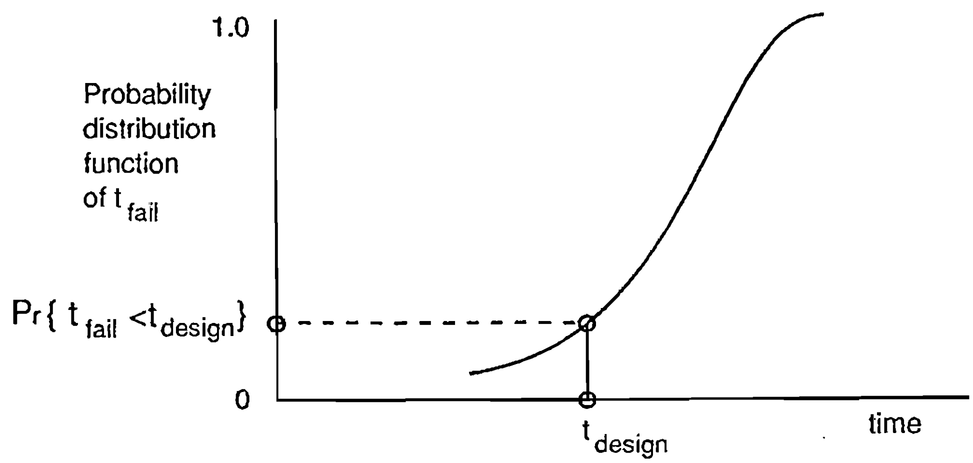

Figure 3. Statistical representation of time to failure.

The variability of the event times should take into consideration not only the natural in-service variability of these events, but also the additional variability that reflects the uncertainties arising from our inadequate knowledge or from the use of simplified models. Of particular interest is the risk parameter $P_r\{t_{fail} < t_{design}\}$, the probability that the time to failure t_{fail} is less than the specified design life of the structural element, t_{design}. Typical acceptable values of the risk parameter are 0.05, 0.2, and 0.5 for structural collapse, unserviceability and aesthetic deterioration respectively.

3. DISCUSSION

3.1 The Attack Scenario

The most important aspect in the development of a design model is the choice of an attack scenario. Once this is done, all past experience and research data may be used to quantify the event times for such a scenario.

3.2 Role of Index Properties, Mapping and Field Studies

Index properties, usually measured through the application of standardised protocols, are useful input parameters for a prediction model. Some of these index properties apply only to specific materials or specific locations and hence their applicability is similarly limited. An example of this would be index properties derived for specific species in a standard grave yard test. More useful for modelling purposes are index properties that can be computed for any situation from readily available data, such as for example, the Scheffer climate index.

Mapping may be applied to hazard, climate and soil parameters. If the mapping is comprehensive, i.e. it covers all of Australia, then it may be used directly as an input parameter for the prediction model. If it is not comprehensive, then the data should be used to calibrate a sub-model that acts as a comprehensive input for the prediction model.

Field studies involving full size real buildings or other timber construction will always be limited in scope. Hence the data from these studies should be used only to calibrate generic sub-models as discussed above. *Accelerated field simulators* perform the same role as field studies i.e. they may be used to calibrate durability models. However, since the data here relates to simulation and not to real events, care must be taken to ensure that the attack mechanism is realistic.

4. EXAMPLE: MODEL FOR ATTACK BY DECAY

4.1 Decay Equation

The simplest decay equation, illustrated schematically in Figure 4 is given by

$$dW/dt = f\,(s, m, T, \phi, p, b) \tag{1}$$

where W denotes the distance to the decay front, s denotes an index parameter related to timber species, m denotes a moisture matric potential, T denotes the temperature of the timber, ϕ denotes the osmotic potential of the water if solutes are present, p denotes an index parameter related to the preservative present (if any), and b denotes an index parameter related to the biological agents present (Griffin 1977). If the timber is not in ground contact, then the terms ϕ and b may be omitted.

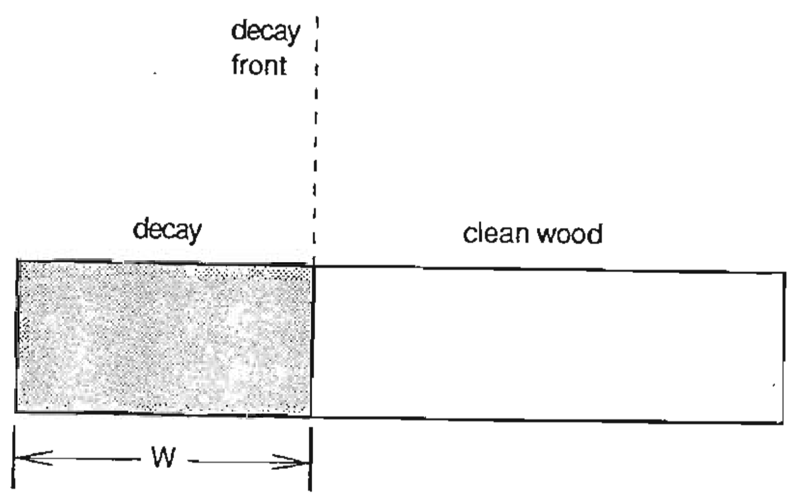

Figure 4. Notation for base model of decay.

4.2 Attack Model

For *timber protected and above ground,* such as timber in buildings, Figure 5, it is necessary to predict moisture content and temperature. This is possible through the use of climate data and heat and mass transfer equations (Künzel and Kieβl 1995). In addition, there are field studies of Australian housing that may be used to calibrate the model (Cole 1993).

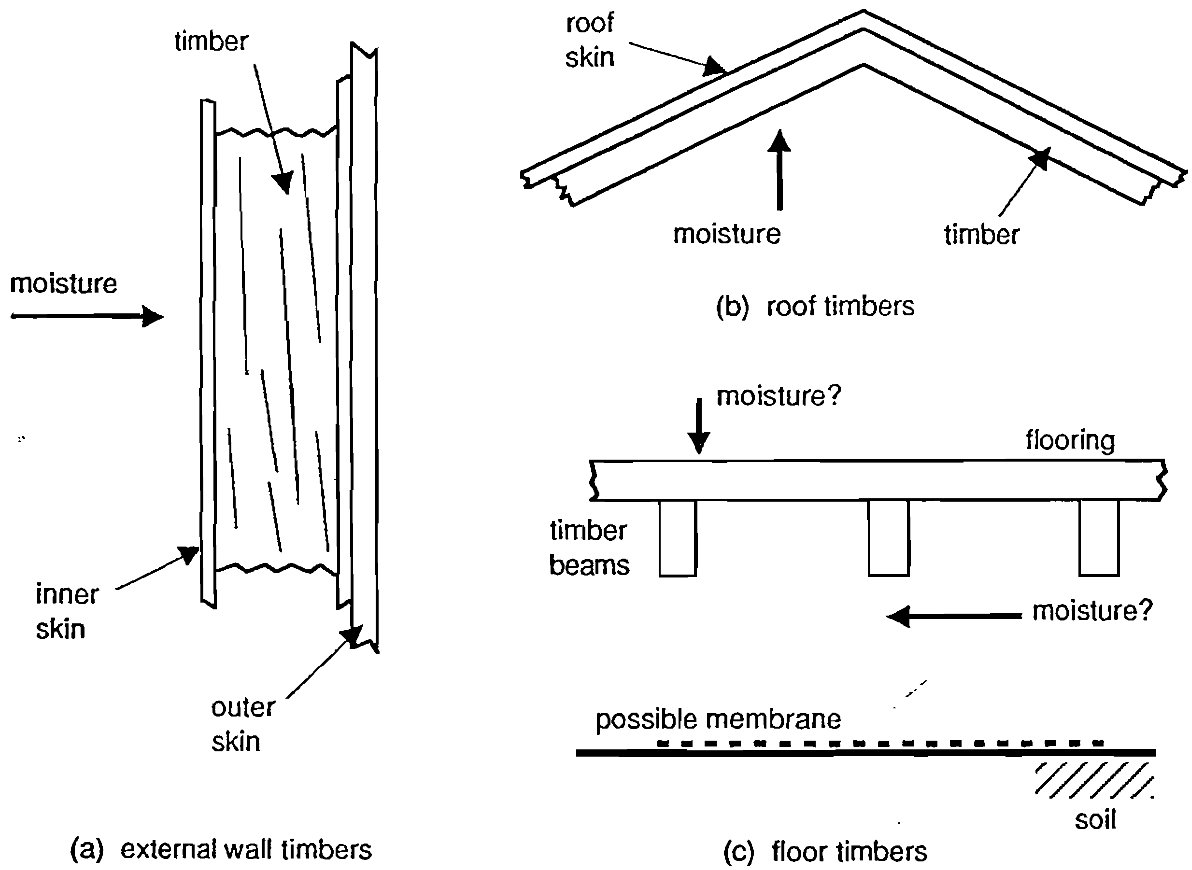

Figure 5. Examples of protected timber.

For *timber above ground,* but exposed to the weather, Figure 6, moisture ingress is largely a function of 'time-of-wetness' arising directly from rain. For a given climate, both the moisture condition within the wood and the temperature of the timber must be predicted (Sutherland *et al.* 1994). The moisture ingress must take into account any surface coating present (Derbyshire *et al.* 1996).

If the timber element has a protective skin arising either from a surface coating or a finite penetration of a preservative treatment, then it is convenient to treat the penetration of decay as two sequential events; the first is the penetration of the skin (Carey 1992) and the second is the attack on the inner core. Field observations indicate that cracking of the timber has a major effect on decay rate. This is partly due to the fact that cracks allow fungal and bacterial spores to bypass the protective skin, and partly because it allows the rain to accumulate and penetrate into the interior of the timber. Hence the penetration of surface cracks is an important part of this model. Data from exposure tests on L-joints, cladding, decking and window frames will provide useful information in the development of this model (Cause and Stringer 1993; Cause 1994; Boxhall 1992; Creffield *et al.* 1992).

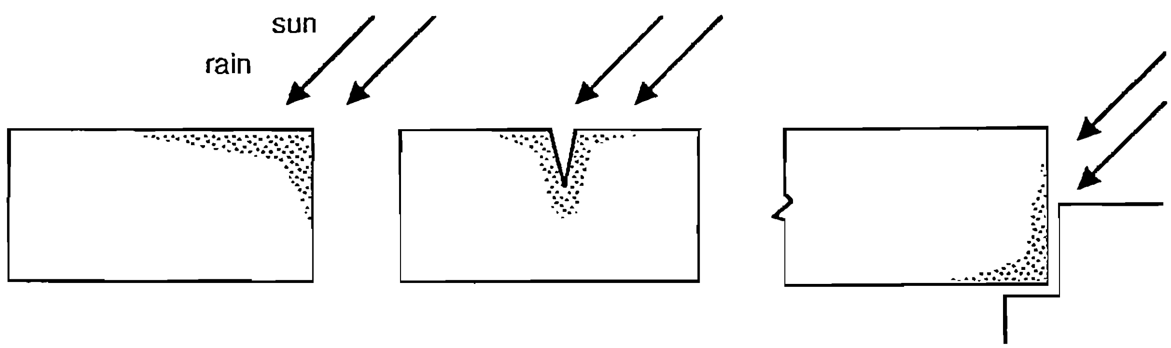

Figure 6. Examples of exposed timber, above ground.

For *timber in ground contact*, Figure 7, the additional concern is the ingress of moisture from the soil. Methods are available to predict soil moisture content on the basis of soil type, climate and surrounding vegetation (Jury *et al.* 1991). Data from long term grave yard tests will be useful for this model (Thornton *et al.* 1994). However to do this effectively, it may be necessary to first estimate the moisture and temperature history of the test stakes. In addition, there is some debate as to whether the biological agents of decay vary significantly with soil type and/or region.

5. FUTURE

To facilitate progress, development of the model will be focussed initially on a limited set of building elements. These include bridge girders, power poles and cross-arms, exposed shoes for glulam arches, sub-floor stumps, domestic decking and cladding, pergolas, fencing, external joinery and wet area floors.

Work on the models has only recently commenced. Some 350 published papers have been obtained that contain information relevant to the development of quantified models. Contact has been established with a few overseas groups working in similar or related fields. Hopefully, in the future an effective network for collaborative work on this topic will be established.

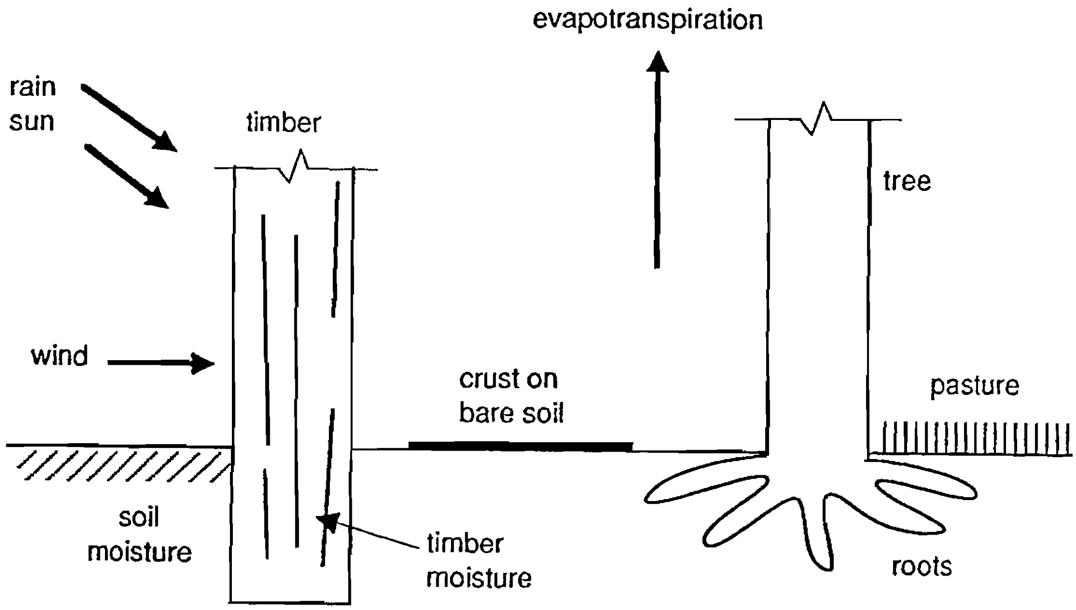

Figure 7. Illustration of exposed timber, in ground contact.

6. ACKNOWLEDGMENTS

The durability model is intended to encompass and reflect current knowledge. Accordingly, the author is indebted to the numerous durability experts who are so generously assisting in this work.

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2. MICROWAVE ACTION

Useful studies on the fundamental action of microwaves in wood are reported in papers by Kharaldy (1985) and Yen (1981). For practical application, the microwaves are transmitted as polarised waves. If the transmitted wave is polarised in a direction either parallel or perpendicular to the grain direction of the wood, then as it travels through the wood, in the z-direction, the amplitude A and phase ϕ of the wave is given by

$$A = A_o \exp(-\alpha z) \tag{1a}$$

$$\phi = \phi_o - \beta z \tag{1b}$$

where A_o and ϕ_o denote the values of A and ϕ at the surface $z = 0$, and α and β are constants related to microwave frequency, the timber species, density and moisture content.

If the transmitted wave is polarised at an angle θ to the wood grain, cross-polarisation takes place and a complex elliptically polarised wave is transmitted through the wood (Yen, 1981).

3. THE COMMERCIAL PROTOTYPE

The prototype commercial stress-grader is illustrated schematically in Figure 1. It includes two sets of microwave scanners comprising a knot detector unit (KD) and a slope-of-grain measurement unit (SOG); these units are placed in line with a mechanical stress grading unit (MSG).

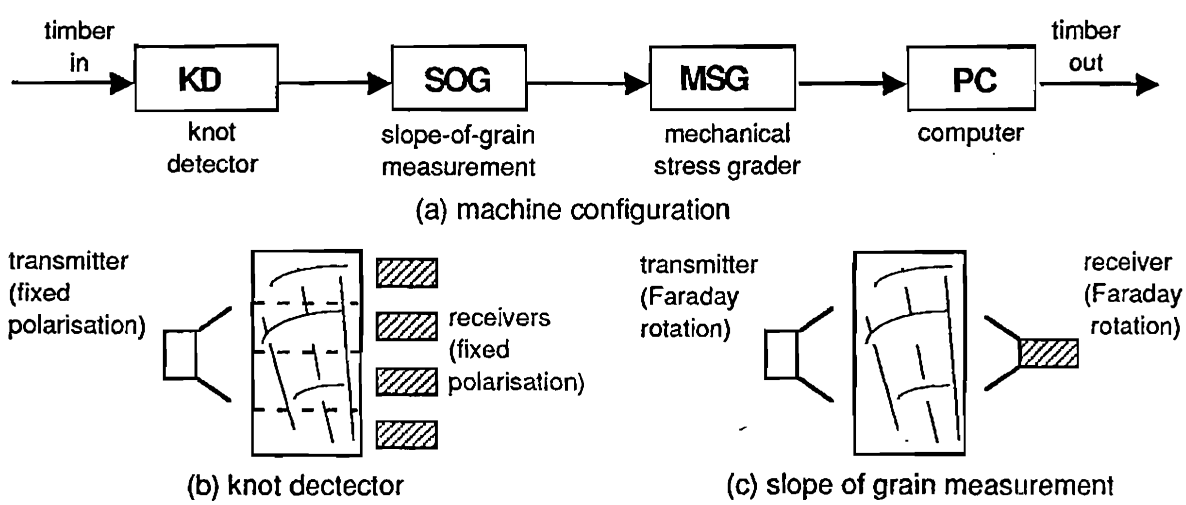

Figure 1. Schematic illustration of stress-grader.

An operating frequency of 10 GHz was selected for the microwave equipment; this represents a compromise between high frequency requirements for the detection of small defects and low frequency requirements for ease in the design and manufacture of electronic hardware. At this frequency, the occurrence of defects as small as 10 mm width can be detected. The scanners are low power scanners, safe to use, with an output of about 0.15 watts each; however, at this low power level, they are suitable only for timber with a moisture content below the fibre saturation point.

For the prototype, the KD unit comprises a single transmitter plus a bank of four receivers as shown in Figure 1(b); the transmitter and receivers are fixed in position and are polarised at an angle of ±45° respectively to the longitudinal axis of the board. The SOG unit comprises a single receiver and transmitter as shown in Figure 1(c); through the use of Faraday rotators (Caswell 1964; Lance 1964) these transmitter and receivers are locked in the crossed configuration and electronically swept through angles of ±45°. The angle of maximum attenuation is taken as the grain angle.

The prototype equipment operates at a timber throughput speed of about 200 m/min with measurements being made every 6.5, 13.0 and 65.0 mm for the KD, SOG and MSG units respectively.

4. ALGORITHM FOR STRESS GRADING

4.1 General

The most important (and most difficult) aspect of the commercialisation process for a new stress-grading system is to develop a suitable algorithm for sorting timber into various stress-grades.

As each board passes through the grading machine, the system generates six continuous signals of the type shown in Figure 2. Four signals arise from the KD unit, one from the SOG unit and one from the MSG unit. It is these six continuous signals that must be processed to assess the strength of each board of timber.

4.2 Strength of Individual Defects

The first step in the development of an algorithm for grading is to choose an algorithm for predicting the bending strength along the length of a board. This is usually done by breaking each board of a representative population of timber at one or two major defect locations and then fitting a prediction algorithm to the test data.

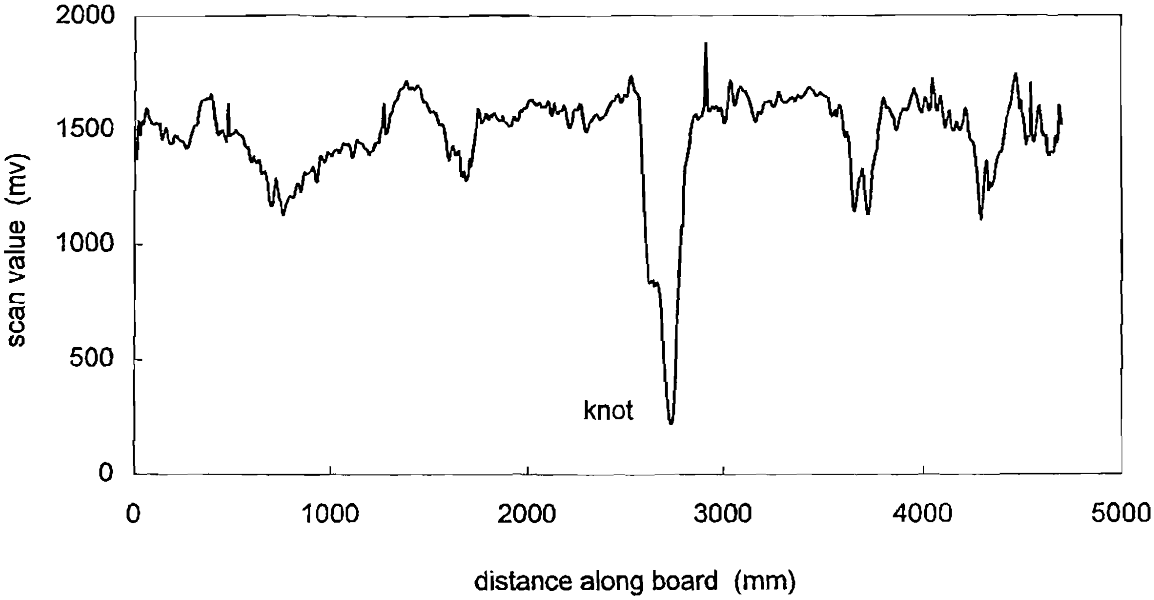

Figure 2. Signal from top receiver of KD unit for board A100.

The simplest procedure for developing the algorithm is to process the continuous signals to provide a set of some 10 to 20 discrete parameters. Typically, two or three of these parameters will be extracted from each data signal. In addition, for the KD signal, some preprocessing was used to convert the signal from a continuous one to a binary signal related to knot detection. The effectiveness of this preprocessing can be judged by comparison of the preprocessed signal with a visual assessment of knot occurrence, Figure 3.

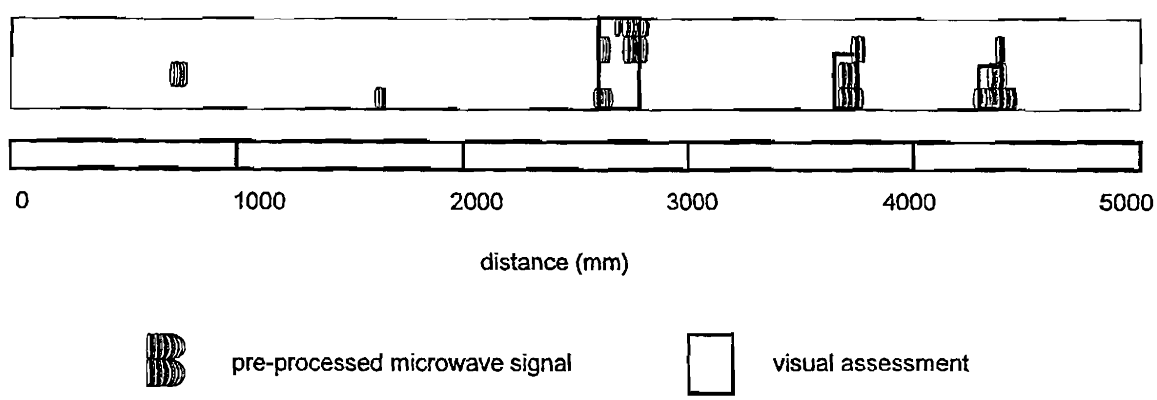

Figure 3. Comparison between visual and microwave assessment of knot presence in board A100.

Once signal parameters have been selected, the desired algorithm can be derived through several methods. Some useful procedures for this are the following

- correlation equations
- neural networks
- variance segmentation.

4.3 Strength of Graded Timber

The simplest procedure for grading timber is to use the stress-grading system to predict the strength along a board of timber, Figure 4. The weakest predicted strength along the board is then taken to be the grade indicator. A complication arises from the fact that in the Australian Standard AS/NZS 4063, it is specified that the bending strength of timber be measured on specimens cut from random locations of stress-graded material, Figure 5. Thus, for a given board, the location of the grade indicator and the location of the bending strength test specimen may not be the same.

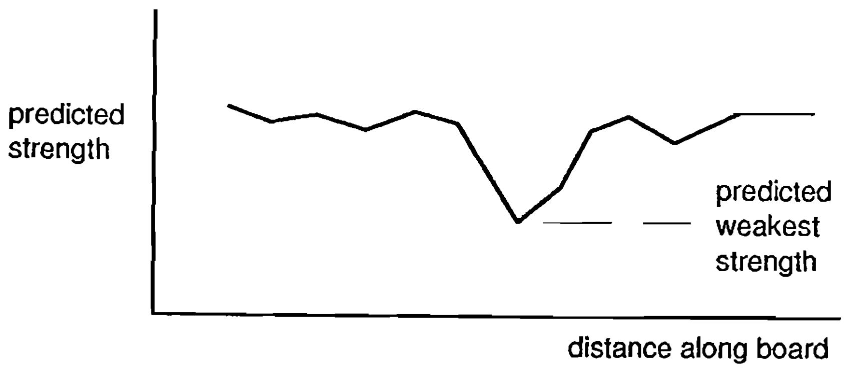

Figure 4. Predicted strength along a board.

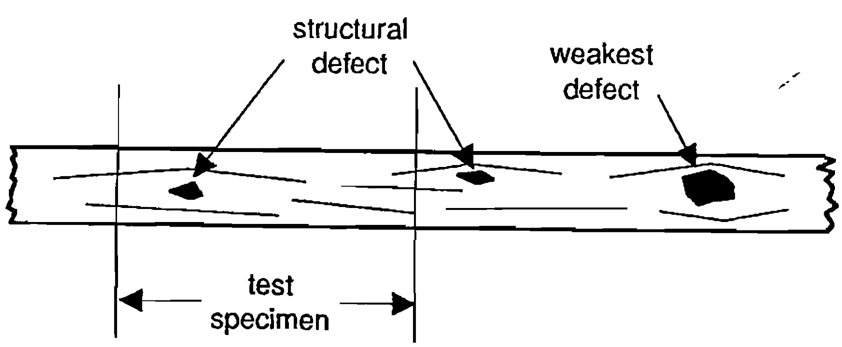

Figure 5. Selection of test specimen for measuring bending strength.

A schematic illustration of a typical stress-grading operation is shown in Figure 6. Here, three grades have been selected. For each grade, the design strength is taken to be proportional to the 5-percentile value.

4.4 Assessment of the Grading Algorithm

Any assessment of the value of a stress grading operation should be made on a comparative basis. For a new system, the most convenient comparison is that of the value of the stress-grading operation before and after the addition of the new scanning equipment.

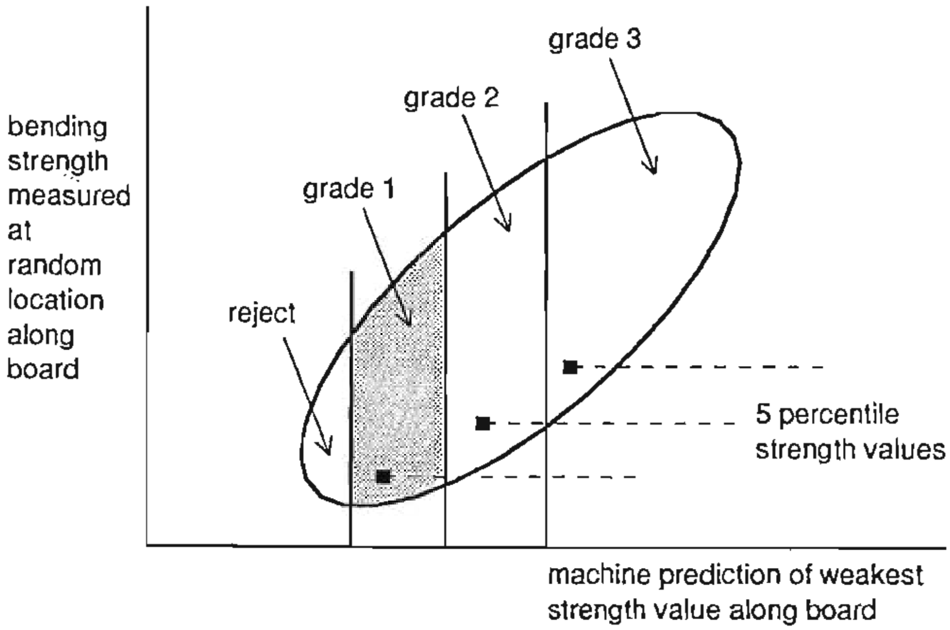

Figure 6. Schematic illustration of a stress-grading operation.

There are essentially two ways of assessing the value of an operation. One method is to assess the recovery of the timber; referring to Figure 6, this would be the quantity of timber in Grades 1–3 relative to the total population of timber. Another method is to assign a commercial value to the timber from each stress-grade, and hence compute a value for the timber in Grades 1–3.

4.5 Refinement of the Algorithm

Obviously the simplifications associated with the use of discrete parameters, and the choice of grade indicator leave considerable scope for improving the efficiency of the algorithms developed as described here. However a considerable quantity of test data may be required to effect these improvements.

Of most practical concern is the robustness of the algorithm used. It is possible that highly efficient algorithms are sensitive to changes in timber resource characteristics; small changes in the resource characteristics may lead to major changes either in structural reliability or grading efficiency. Hence, an issue of considerable practical concern is the development of robust algorithms and of methods for assessing that robustness.

5. COMMERCIALISATION

Once adequate algorithms have been developed, there are still further steps to be covered before full commercialisation is implemented.

The durability of the equipment needs to be confirmed under factory conditions of temperature fluctuations, dust, vibrations and impact (by stray timber boards). In addition, software checks must be installed to detect the occurrence of invalid operating conditions. For example, the microwave scanners used have a very low power output and as a result, do not operate accurately once the moisture content of the wood exceeds 20 per cent.

Finally, process control procedures must be developed, which ensure that the scanning equipment is operating correctly. Fortunately, many of the procedures developed for mechanical stress grading machines, such as ensemble averaging, are in principle, equally applicable to all forms of scanning equipment.

6. STATUS

Experience to date indicates that microwave scanning equipment can be made both robust, consistent and effective and that there are no unsurmountable barriers to be overcome in their commercial application.

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EVALUATION OF MECHANICAL JOINT SYSTEMS IN TIMBER STRUCTURES

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ABSTRACT

This paper discusses the limitations of current Australian standards on evaluation of timber joints and presents a more consistent and realistic method of performance evaluation of mechanical joint systems. The proposed draft standard has four main features: (1) consideration of actual in-service joint configuration; (2) consideration of realistic in-service loads (i.e. dead, live, wind and earthquake loads); (3) consistent method of obtaining characteristic strength and other design properties; and (4) consistent method of application of load factors. Its acceptance will help facilitate performance comparisons of different joint systems.

1. INTRODUCTION

Timber joint code development in Australia has been discussed by Leicester (1993). The need for better and more realistic joint testing and evaluation procedures is highlighted when we review the current joint testing and evaluation procedure for timber structures in Australia, AS 1649 (Standards Australia 1974) and its draft revision DR 83020 (Standards Australia 1983). The structural timber design code AS 1720.1 (Standards Australia 1988) endeavours to give a design procedure for a joint system made up with connectors tested using AS 1649. There are three flaws with this operational system.

- First, the AS 1649 test provides data on only one type of failure mode whereas at least ten types of failure modes have been observed in laboratory tests. Some examples include: (a) failure of metal (tension, bending, shear, buckling), (b) failure of wood parallel to the grain (tension, compression, shear), and (c) failure of wood perpendicular to the grain (tension, compression). An example of major concern is the failure of bolted joints due to splitting; AS 1649 and DR 83020 do not address the problem of splitting.

- The second flaw is that the load factors currently used in AS 1649 and proposed in DR 83020 are questionable. They were derived on the basis of fitting existing practice. It is not known whether the controlling criteria, then in use, were related to strength or serviceability (deformation); also the load factors vary considerably from one connector type to another for no obvious reasons.

- The third flaw in the current procedure arises from the fact that there are very few theories to predict the strength of joint systems on the basis of the characterisation of single connectors. The limited system theories available include the Canadian work on glulam rivets, the Finnish theory on punched metal plates and the New Zealand studies on multi-nail steel and plywood gusset plate systems. Thus, there is obviously a need for a standard not only to describe the testing of new fasteners, but also for *total* joint systems.

If the reliability of joint systems is to be comparable with that of solid timber, then for each joint a set of characteristic strengths must be evaluated for each basic type of load (Fig. 1a). And because there are numerous types of systems for which each single type of connector can be used, it is unlikely that any manufacturer will undertake a comprehensive set of tests. This will also create obvious difficulties in obtaining harmonisation of design rules for connectors in various countries.

One solution would be to draft a set of evaluation methods of complete joint systems that (1) specifies actual in-service joint configuration (e.g. Fig. 1b); (2) specifies realistic in-service loads (e.g. Figs. 1a and 2); (3) has a consistent method of obtaining characteristic strength; and (4) has a consistent method of applying load factors to obtain joint design properties. The spirit of this set of joint systems standard should be analogous to AS 4063: Timber—Stress-graded—In-grade Strength and Stiffness Evaluation (Standards Australia 1992), i.e. it may be used to test any joint under any loading configuration *but* it is not necessary to test every joint under every loading configuration.

The draft standard AS BBBB (Timber—Evaluation of Mechanical Joint Systems, Part 1– Static Loading; Part 2– Cyclonic Wind Loading; Part 3– Earthquake Loading) is a set of standards with all the above features (Standards Australia 1996). General information about this set of standards (collectively called herein as 'the draft standard') are discussed in this paper. While the proposed draft standard was initially conceptualised and drafted in CSIRO, representatives of other institutions [BRANZ (e.g. Deam 1995), Monash University, NZFRI and University of Technology Sydney] have made some contributions to the current version of the proposal.

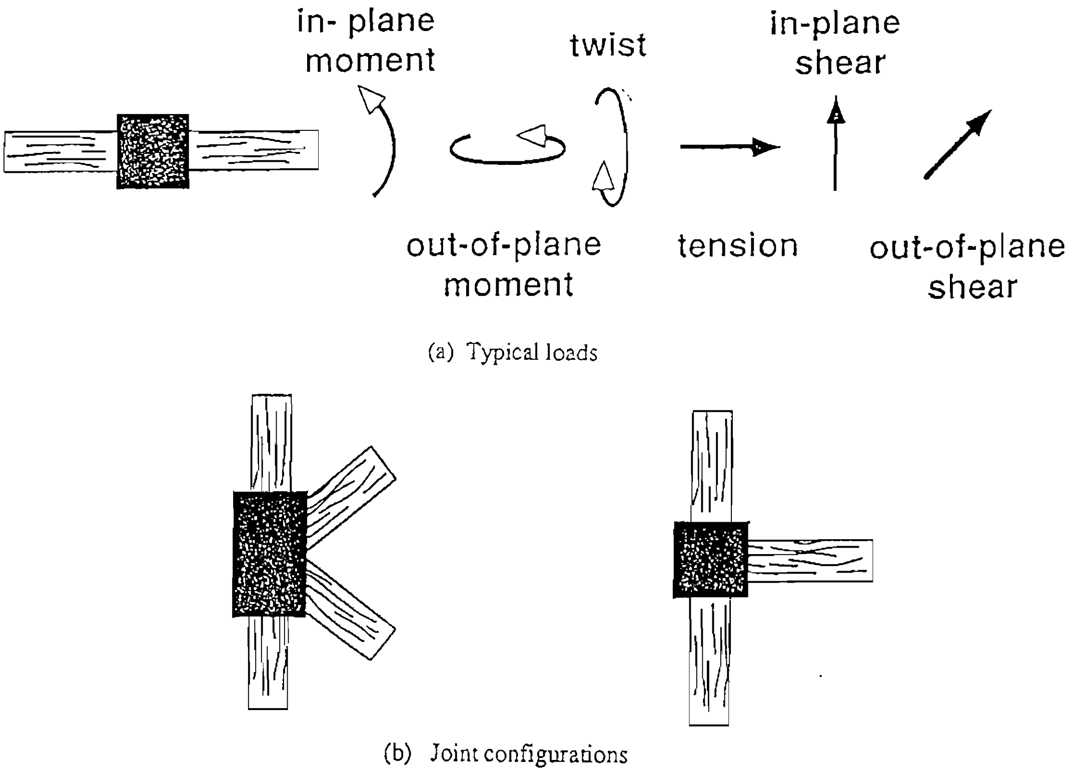

Figure 1. Examples of loads and configurations of structural joint systems.

2. APPLICATIONS OF PROPOSED STANDARDS

The draft standard is intended to establish the design properties and/or evaluate the performance of a specific joint system under gravity (dead and live) loads, non-cyclonic and cyclonic wind loads and earthquake loads. This can be used for individual fastener types (e.g. nails, bolts, screws, etc.) or jointing systems (i.e. complete joint system of similar or mixed materials). Data derived will be for a particular material group (e.g. timber species or species group).

For *fastener* types under specific loading, this set of standards can be used to:

(a) allocate general design properties to a new type of fastener under a specific loading configuration; and

(b) check or assess design properties for existing or common fasteners in specific structural situations.

For *jointing systems* under specific loading, this can be used to:

(a) assess the performance and allocate design properties of a joint system under a specific loading configuration; and

(b) assess design theories for joint systems.

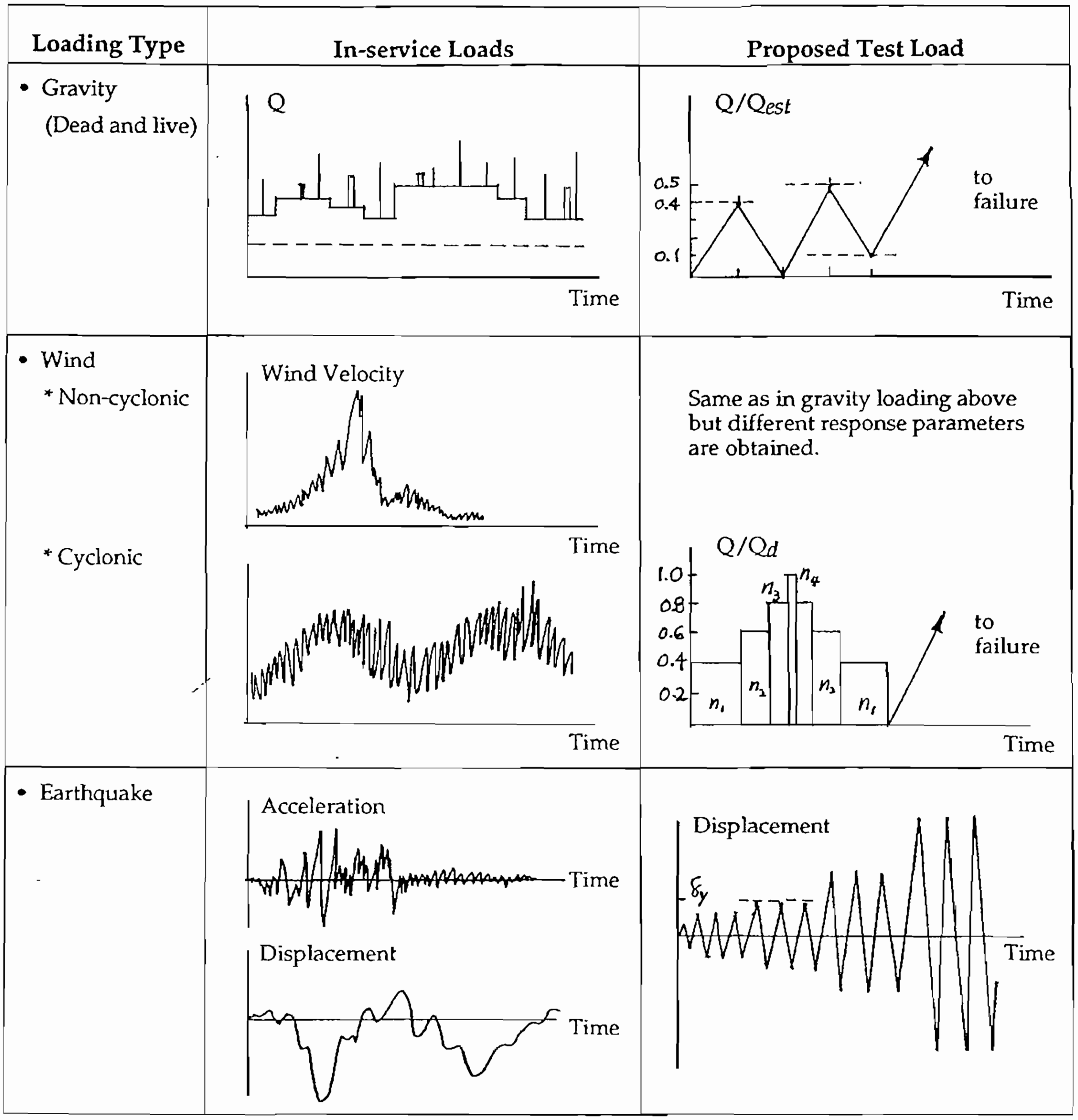

Figure 2. Examples of in-service loads for structures and proposed test loads.

And for *fastener types and/or jointing systems* under combined loading, this standard can be used to assess the performance of fastener types and/or jointing systems required to transmit a range of load types (e.g. moment, shear) acting in combination at a range of intensity.

'Load' and 'deformation' are taken as generic terms. Load could be moment, shear, axial or torsion or any of these acting in a fixed ratio combination. Deformation could be slip, elongation, shortening or rotation.

3. TEST SPECIMENS AND APPARATUS

In the draft standard, test samples are to be representative of the population from which they are drawn. The joint specimens are to be fabricated in such a way that they correspond in a realistic manner to the joints expected in practice, with regards to geometry, gaps, fastener tolerances, etc. They are to be fabricated in their normal environment and conditioned to the moisture content and temperature they are expected to be in service unless special test conditions are required.

The joint is to be installed in a suitable test machine and arranged such that it will be loaded in the same manner as it would be in practice. Care should be taken to ensure that undesirable or unrepresentative secondary forces will not be applied to the joint. Measurements of load and deformation for the complete joint should be recorded, preferably continuously, throughout the test.

4. LOAD APPLICATION

Test loads are selected to simulate actual in-service loads. This means that to evaluate joint performance under cyclonic wind loading, a repeated loading history such as that proposed by Mahendran (1995), slightly revised and shown in Fig. 2 (right-most column) is to be used. The number of cycles to be applied per load level will depend on the joint's location in the building; that is, more cycles are required for roof joints than for wall joints (see the draft standard for details). For joints under normal gravity loading and noncyclonic wind loading, a monotonic loading regime with initial pre-loading (Fig. 2) is recommended. For joints under earthquake loading, a full-reversal (through-zero) cyclic loading regime is to be used (Fig. 2).

Some guidance on the rate of load application is given in the draft standard but, if desired, the loading rate may relate to loading conditions that it is known the joint will experience in service.

The draft standard recognises that the choice of test procedure, and associated loading history, depends on the purpose of testing, type of test specimen or structure where the specimen is to be used and type of anticipated failure mode. Thus, it allows the use of other test procedures that address test objectives different from those of the recommended procedures. Examples of alternative procedures are outlined in the Appendices of the draft standard.

5. TEST RESULTS AND DATA ANALYSIS

Details on the set of data that needs to be recorded in the course of the test, the parameters that need to be computed and all the information required in the test report are given in the draft standard. The recommendations on methods of obtaining characteristic strengths and other design properties and application of load factors are based on the work by Leicester (1986; 1987). However, other methods of obtaining characteristic properties can be used (e.g. see Hunt and Bryant 1996) as long as the specified target (e.g. in the case of strength, 'fifth-percentile value with 75% confidence') is maintained.

5.1. Stiffness and Ductility

The characteristic value (M_k) of stiffness, for all load cases, and ductility, for earthquake design, are to be computed as the mean value, with 75% confidence, of measured stiffness and computed ductility. These can be used in both limit states codes and working stress codes.

The characteristic value can be computed by the following:

$$M_k = [\,1 - (0.7\,V / \sqrt{N}\,)\,]\,M_{\text{mean}}$$

where M_{mean} is the calculated mean value from the test data; V is the coefficient of variation of measured data; and N is the number of specimens in the test series.

5.2 Strength; Specified Load Capacity for Limit States Codes

The characteristic strength estimate (R_k) is to be based on the fifth-percentile ultimate load (Q_u) value with 75% confidence.

For N < 10, the characteristic strength estimate R_k can be computed by

$$R_k = R_{\min}\,(N/27)^{V_e}$$

where $R_{\min}$ denotes the minimum Q_u measured in a sample of size N, and V_e is an estimate of the coefficient of variation of Q_u (e.g. based on experience or an informed guess).

For $N \geq 10$, the characteristic strength estimate R_k can be computed by

$$R_k = [\,1 - (2.7\,V \,/\, \sqrt{N}\,)\,]\,R_{0.05}$$

where $R_{0.05}$ is the fifth percentile value of measured data and V is the calculated coefficient of variation of Q_u from the test data.

The nominated load capacity $R_{k,\text{nom}}$ for design codes is then obtained by applying a load factor for joint systems. Regardless of sample size, this can be computed by

$$R_{k,\text{nom}} = \frac{1}{\phi}\,(0.85 - 0.95\,V)\,R_k$$

where ϕ is the value of capacity factor specified for use with this type of mechanical fastener.

5.3 Strength; Specified Load Capacity for Working Stress Codes

The specified load capacity for working stress codes (R_{bws}) is given by

$$R_{bws} = \frac{1}{1.35\,k_d}\,(0.85 - 0.95\,V)\,R_k$$

where k_d is the duration of load factor for 50 years.

6. CONCLUDING SUMMARY

To address the limitations of, and inconsistencies in, current Australian standards on evaluation of timber joints, a new set of standards has been proposed. It has four main features: (1) consideration of actual in-service joint configuration; (2) consideration of realistic in-service loads; (3) consistent method of obtaining characteristic design properties; and (4) consistent method of application of load factors.

The draft standard may be used to test any joint under any loading configuration *but* it is not necessary to test every joint under every loading configuration. It can be used to establish the design properties and/or evaluate the performance of a specific joint system under gravity (dead and live) loads, non-cyclonic and cyclonic wind loads and earthquake loads. Both/either individual fastener types (e.g. nails, bolts, screws, etc.) and/or jointing systems (i.e. complete joint system of similar or mixed materials) can be tested. Its acceptance will help facilitate performance comparisons of different fasteners and joint systems.

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END-NOTCHING EFFECT ON FLEXURAL STIFFNESS OF NORTH AMERICAN SAWN TIMBER

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ABSTRACT

Full-size beams of Southern yellow pine and yellow poplar were nondestructively loaded in flatwise bending, notched at the end and destructively loaded in edgewise bending. Flatwise beam stiffness measured before notching was adjusted to its equivalent edgewise stiffness and compared with experimental results. Preliminary tests show that stiffness of end-notched wood beams was influenced by span-to-depth ratio, fractional notch depth and notch location. The effect of end notching on beam stiffness of sawn timber has not been seriously addressed before and theoretical analysis does not predict the reduction.

1. INTRODUCTION

The evolution of material use, design approach and construction techniques in timber engineering is leading some researchers and authorities to reexamine current deflection criteria and reassess current research priorities (Session 1984). Some propose a balanced emphasis on ultimate capacity and serviceability of structural timber elements. The latter sometimes govern the design of timber beams.

Timber beams are often notched to bring top surfaces to desired levels, allow for necessary clearance and/or fit support or framing conditions. While the stiffness of timber beams has long been an area of special interest, end-notching effect on timber beam stiffness has not been experimentally investigated. Design codes and standards do not specifically address this issue. It is commonly accepted that deflection of timber beams will hardly be affected by end-notching since "it is a function of the summation of *EI*" (*E* is the modulus of elasticity and *I* is the moment of inertia) (Ozelton and Baird 1976). Results of a finite element (FE) study by Abou-Ghaida and Gopu (1984) on end-notching effect on timber beam stiffness corroborated this statement. They explained that "the loss of section at the end region does not, for all practical purposes, alter the angle change *(M/EI)* diagram for the member" (Abou-Ghaida and Gopu 1984).

The stiffness of timber beams with tension interior notches had been theoretically and experimentally investigated and methods of quantifying the effect of interior notching on stiffness have been proposed (Abou-Ghaida and Gopu 1984; Gerhardt 1984; Hirai and Sawada 1979a; 1979b; Murphy 1986; Sugiyama and Maeda 1990). With end-notching on the tension face, however, theoretical analyses do not show an effect on timber beam stiffness. This study was aimed at experimentally determining any effect. End-notching effect on strength has been reported elsewhere (Foliente and McLain 1992a; 1992b).

2. MATERIALS

Two materials were selected to represent anatomically different North American softwood and hardwood species groups: Southern yellow pine *(Pinus* spp.) and yellow poplar *(Liriodendron tulipifera).* All pine materials were purchased kiln-dried from a lumber yard in Virginia, USA. All poplar materials were purchased kiln-dried from a Virginia mill. Full-size bending specimens measuring 89 x 38 x 1190 mm (3.5 x 1.5 x 47 in.) and 228 x 38 x 1190 mm (9 x 1.5 x 47 in.) were prepared. Most specimens had minimal defects (i.e. American select structural grade); none contained defects near the notch. Filleted notches were cut as described by Foliente and McLain (1992a).

For pine, the average moisture content and average specific gravity on ovendry weight and volume basis were 11.4% and 0.54, respectively; for poplar specimens the averages were 7.7% and 0.50, respectively.

3. STIFFNESS MEASUREMENTS

All bending tests were conducted using an MTS servohydraulic test machine under stroke control. In all cases, the load was applied continuously at the center of a 1.07 m (42 in.) span. Nomenclature for end-notched wood beams is given in Figure 1.

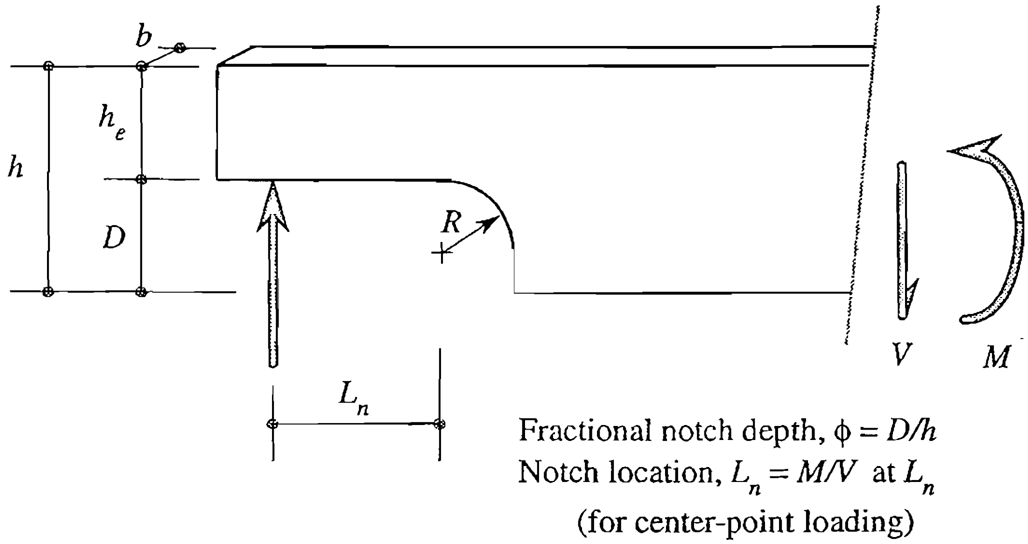

Figure 1. Nomenclature for timber beam with filleted end notch.

3.1 Before Notching

Sixteen defect-free, prismatic boards were separated for each species. These boards were tested flatwise with a center-point bending load at a constant deflection rate of 13 mm/min. Beam deflection was measured from crosshead movement. In most cases, testing was terminated before a 2.67 kN load is applied. From the $P-\Delta$ curve, stiffness values (P/Δ) were measured and recorded for each beam. The beams were labeled and distributed to the experimental block identified below. Gerhardt (1984) showed that the experimental stiffness of wood beams with tension interior notches was not significantly affected by notch fillet radius, R; thus, with tests of end-notched beams, R was fixed at 6 mm. Two beams were assigned for each cell with the following parameters:

variable	levels
h (mm)	89, 228
M/V (mm)	125, 254
ϕ	0.20, 0.50
species	pine, poplar

Flatwise bending was used to calculate true modulus of elasticity, $E_{t,flat}$, from measured stiffness because edgewise testing a beam with low L/h ratio (e.g. 4.67 for beam with $h = 228$ mm) may cause damage that could influence the response of the beam after notching.

3.2 After Notching

The test beams, after notching, were subjected to an edgewise, center-point bending load under a constant rate of motion of the crosshead of 2.5 mm/min. All beams were tested to failure. A bearing block with contact radius of 203 mm was used in testing 89 mm-deep beams and a block with 560 mm contact radius was used for 228 mm–deep beams. In the latter case, lateral support at midspan was provided to restrict lateral movement. The support was designed to allow vertical movement with minimum frictional restraint. Load-deflection ($P - \Delta$) curves were obtained for each test using a linear variable differential transformer (LVDT), attached at midspan of a lightweight deflection yoke, and an X–Y plotter. Stiffness calculations are described in the next section.

Support at the notched end was adjusted for each combination of h and ϕ so that all test beams were level before load application. A 50 mm wide aluminium bearing block was placed at the supports to minimize compression. The blocks were attached to tubular steel supports which were free to roll, thus minimizing axial constraint. With center-point loading, a beam with notch flush at the support has M/V = 25 mm.

4. CALCULATIONS

From the measured flatwise stiffness (P/A) of the unnotched samples, the 'true' modulus of elasticity, $E_{t,flat}$, for each board was calculated as

$$E_{t,flat} = \left(\frac{P}{\Delta}\right)\left(\frac{L^3}{48I}\right)\left[1 + 1.2\left(\frac{b}{L}\right)^2 \frac{E}{G}\right] \tag{1}$$

where I is flatwise moment of inertia ($hb^3/12$) and E/G is orthotropic ratio [13 for pine (Goodman and Bodig 1970); 14 for poplar (USDA 1987)]. The shear correction for flatwise loading was less than 2%.

For unnotched beams, the 'true' edgewise modulus of elasticity is

$$E_{t,edge} = \lambda \, E_{t,flat} \tag{2}$$

where λ is an empirically determined adjustment factor which is dependent on lumber species, MC, grade and size. Experimental data on Southern pine materials of equivalent MC, grade and size indicate that $\lambda \approx 1$ (McLain *et al.* 1984); thus, it was set to unity. The same was assumed for poplar samples. From Eqs. [1] and [2], an equivalent edgewise stiffness of the unnotched board was calculated as

$$\left(\frac{P}{\Delta}\right)_{un} = \frac{48E_{t,edge}\,I}{L^3\left[1 + 1.2\left(\frac{h}{L}\right)^2 \frac{E}{G}\right]} \qquad (3)$$

where I is the edgewise moment of inertia ($bh^3/12$).

After the boards were notched and destructively tested, stiffness values were measured and recorded as $(P/\Delta)_n$. To determine a change in stiffness of a board due to notching, the ratio of edgewise stiffness after notching, $(P/\Delta)_n$, to the effective edgewise stiffness before notching, $(P/\Delta)_{un}$, was calculated. Using the formula for calculating apparent modulus of elasticity (E_a), which is the form used in engineering design, the ratio is written as

$$\frac{\left(\frac{P}{\Delta}\right)_n}{\left(\frac{P}{\Delta}\right)_{un}} = \frac{\frac{48E_a I_{eff}}{L^3}}{\frac{48E_a I}{L^3}} \text{ or } \left(\frac{I_{eff}}{I}\right) \qquad (4)$$

where I_{eff} is the effective moment of inertia for the end-notched beam of the geometry from which $(P/\Delta)_n$ was measured. (Note that I_{eff} is not necessarily equivalent to the moment of inertia of the beam net section at the support.)

Table 1 presents the calculated stiffness ratios for pine and poplar materials using Eq. [4]. Practically, $(I_{eff}/I) \leq 1.0$. A ratio of 1.0 means that notching did not affect the stiffness of the beam. A ratio greater than 1.0 is practically unrealistic because the moment of inertia of a board is not logically increased by notching and should, therefore, be interpreted that there is no effect. This occurred only in the I_{eff}/I ratios for the 228 mm deep pine beams (last column in Table 1). The possible cause of this could be one or a combination of some or all of the following: (a) incorrect assumption for the value of λ in Eq. [2] for the 228 mm deep pine beams, (b) incorrect assumption of E/G for pine materials used in the test, (c) lack of beam symmetry (only one end of tested beams has notch), and (d) slight inaccuracy of E_t-values calculated by Eq. [1], a form derived from strain energy analysis based on a first-order shear deformation theory. In any case, this may be interpreted to mean that end-notching of the 228 mm deep pine beams (L/h = 4.67) did not affect its stiffness, except when ϕ =0.50 and M/V = 254 mm.

Table 1.
Approximate stiffness ratios between a notched and an unnotched beam, (I_{eff}/I)

ϕ	M/V (mm)	Spec. No.	$\frac{I_{eff}}{I}$ h = 89 mm (L/h = 12)	$\frac{I_{eff}}{I}$ h = 228 mm (L/h = 4.67)
Species: Southern Yellow Pine				
0.20	25	1	1.03	1.31
		2	0.94	1.34
	254	1	0.86	1.11
		2	0.94	1.14
0.50	25	1	1.00	1.08
		2	0.90	1.40
	254	1	0.56	0.50
		2	0.53	0.74
Species: Yellow Poplar				
0.20	25	1	0.91	0.99
		2	0.97	1.03
	254	1	0.94	0.90
		2	0.82	0.96
0.50	25	1	0.87	0.73
		2	0.92	1.02
	254	1	0.53	0.51
		2	0.53	0.55

Other stiffness ratios for both pine and poplar materials show a definite end-notching influence on beam stiffness, which seemed to be largely caused by fractional notch depth (ϕ) and notch location (M/V). Others have observed similar effects on beams and with tension-side interior notches (Gerhardt 1984; Hirai and Sawada 1979a; 1979b). With end-notched beams, a more comprehensive testing program of beams of different species with numerous levels of L/h, ϕ and M/V is needed to confirm these preliminary results. If verified, deflection calculation methods for interior-notched beams could be modified for use with end-notched beams, or an empirical relationship could be established between beam deflection and notch geometry factors for end-notched beams.

5. CONCLUSION

Stiffness values of full-size Southern yellow pine and yellow poplar beams, with span-to-depth ratios of 4.67 and 12.0 in edgewise bending, were compared before and after notching at the end. Stiffness of wood beams was reduced by end-notching in some cases. Limited tests showed that the magnitude of reduction was influenced by span-to-depth *(L/h)* ratio, fractional notch depth (ϕ) and notch location *(M/V)*. This experimental finding is important because the effect of end notching on beam stiffness has not been seriously addressed before and theoretical analysis does not predict the reduction. Further tests are recommended to establish practical relationships between stiffness reduction and variables *L/h*, ϕ and *M/V* for design purposes.

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AUTOMATED RECOVERY OF TRUSS AND HOUSE FRAME COMPONENTS FROM MACHINE GRADED LUMBER.

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ABSTRACT

This paper describes some preliminary work done to determine the benefits of an automatic house truss and frame cutting machine to recover graded components using grade marks on machine graded lumber.

Roof trusses and house frames are normally constructed using components cut from commodity graded lumber. In commodity grading the structural grade of any individual piece is governed by the worst defect in the piece. This means that although a full length of timber may contain many useful structural components, a small section of a lower grade will cause the full length to be downgraded to the lower grade.

The problem with the commodity grading approach is that customers are buying packets of select length lumber to cut into shorter components while sawmillers are left with large volumes of lower grade lumber which contain many pieces suitable for use as house truss or frame componentry.

This study investigated an alternative approach to commodity grading, called *component yield potential grading*. The concept is not new as component yield potential is used when grading random width lumber according to WWPA grading rules. Component yield potential is new, however, when applied to structural lumber. The idea involves grading and selling packets of machine graded lumber in terms of the number of standard trusses or frames that can be made from a packet.

In New Zealand machine grade yields are decreasing, mainly due to a reduction in rotation age and a change in silviculture. The limited applications for lower grades of lumber results in a large price differential, currently about A$70 per cubic metre, between F4 and F5. The main advantage of component yield potential grading is that it gives sawmillers more flexibility to meet the market needs for structural components.

Lumber sizes used in house frames and trusses were matched to lumber supply options in order to determine the benefits of alternative component recovery strategies. The study concluded that there are benefits in extracting machine stress graded components from lower lumber grades, but the economics depend on the length and quality of the lumber. The potential for component yield grading depends on the adoption of suitable machinery to relate stress graded lumber to component order files. It remains to be seen if component cutting stays with merchants or whether sawmills will offer a cutting service.

INTRODUCTION

Roof trusses and house frames are normally constructed using components cut from commodity graded lumber. In commodity grading the structural grade of any individual piece is governed by the worst defect in the piece. This means that although a full length of timber may contain many useful structural components, a small section of a lower grade will cause the full length to be downgraded to the lower grade. The graded lumber is sorted by grade, and often by length as well, before being distributed. The full packets of lumber are traded as a commodity.

In New Zealand the full packets of commodity graded lumber are purchased mainly by merchants who will often do some sorting or pre-cutting themselves before on-selling the lumber to builders and pre-cut plants.

The problem with a commodity grading approach is that customers buy full length lumber to cut into shorter structural components and sawmillers are left with large volumes of lower grade lumber which contain many pieces that may be suitable for structural componentry. Some mills recover fixed length studs or finger jointing stock from the lower grades while others sell the lower lumber grades to operators who cut it into components.

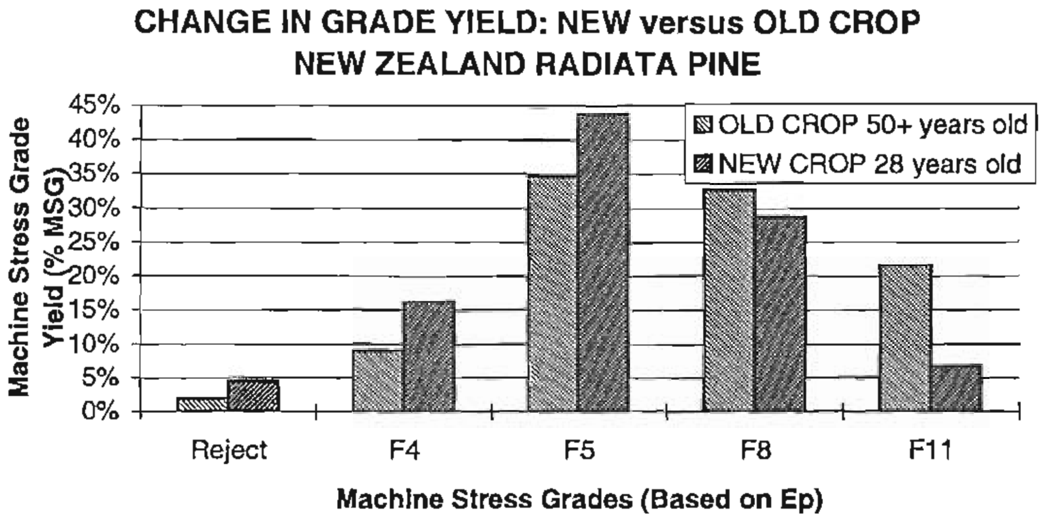
This study investigated an alternative approach to commodity grading called *component yield potential grading*. The concept is not new as component yield potential is used when grading random width lumber according to WWPA grading rules. Component yield potential is new, however, when applied to structural lumber. The idea is to grade and sell packets of machine graded lumber in terms of the number of standard trusses or frames that can be made from a packet. The packets of lumber can be allocated to truss or house frame manufacturing plants operating automatic truss and house frame cutting machines. These operators make use of the grade paint marks on machine graded lumber to recover graded components. The ability to read the machine grader information is an essential part of component yield grading as it allows the recovery of mixed grades to be automated.

The main advantage of component yield potential grading over commodity grading is that it gives the sawmiller more flexibility to meet the market needs for structural components.

RESOURCE CHANGE

New crop machine grade yield are dropping as shown in Figure 1, and this is mainly due to a reduction in rotation age and a change in silviculture. Figure 1 illustrates the difference between MSG yields from old resource (old crop) and younger stands (new crop) currently harvested, based on two FRI studies. The actual values will differ between sites, but the general trend applies to all sites. Because of the limited applications for lower grades of lumber, sawmillers are finding it difficult to sell machine stress graded (MSG) F4. The poor demand for this grade has resulted in a large price differential, currently about A$70 per cubic metre, between F4 and F5. The actual grade yield depends on a large number of factors, but in general, the trend is to recover less F5 and better, and more F4 and Reject.

Figure 1.



Source: FRI database

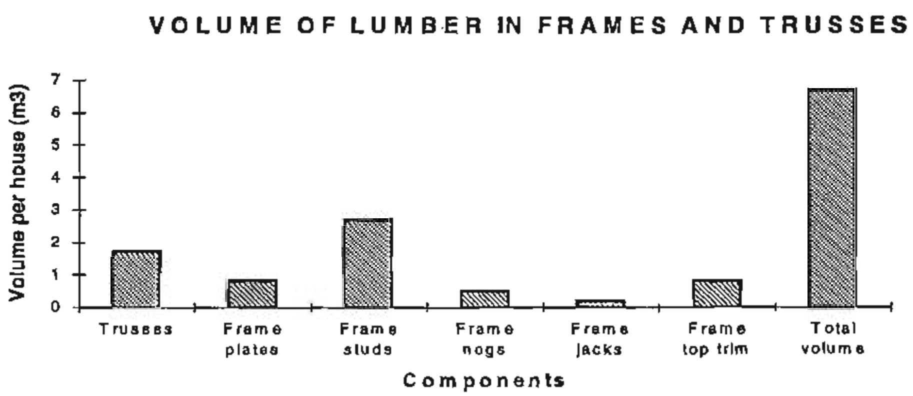
LUMBER SIZES USED IN FRAME AND TRUSS CONSTRUCTION

Typical lumber sizes used in house frame and truss construction were obtained from commercial cutting sheets. Because of the large range of house designs it was decided to select a "typical" modern New Zealand house containing about 7 cubic metres of sawn timber in the frames and roof trusses. The wood used in the flooring system was excluded from this study as many houses are built on a concrete platform.

From this data it was possible to establish the market potential for short lengths and the common uses of structural timber.

Figure 2 shows the volumes used by the various frame and truss components based on the data sheets analysed. As can be seen from Figure 2 nearly half of all lumber is used as frame studs.

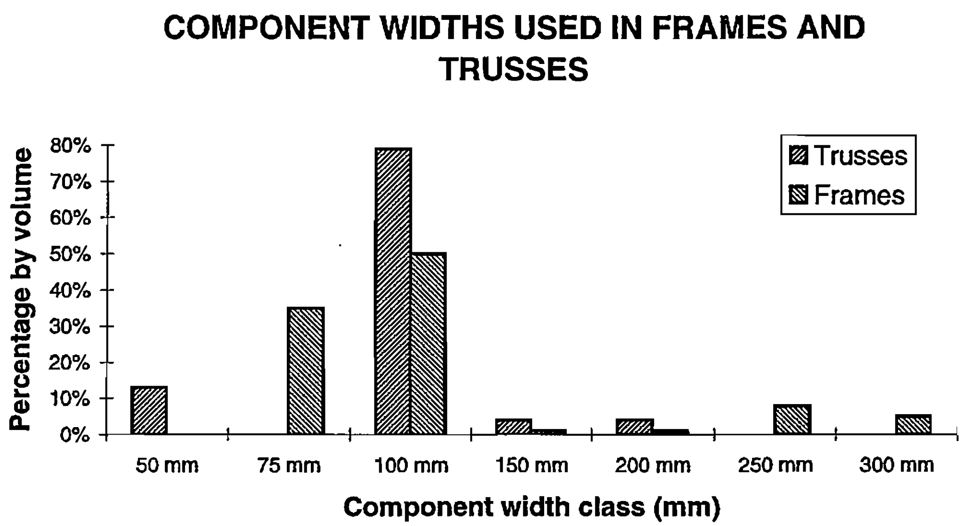
Figure 2



Source: Analysis of commercial cutting sheets by authors.

Typical widths used in frame and truss construction are given in Figure 3. The most popular width is 100 mm nominal (95 mm kiln dried gauged). In the house and truss designs analysed over 80% of all components were 40 mm thick nominal (35 mm kiln dried gauged), therefore this thickness was adopted for this study.

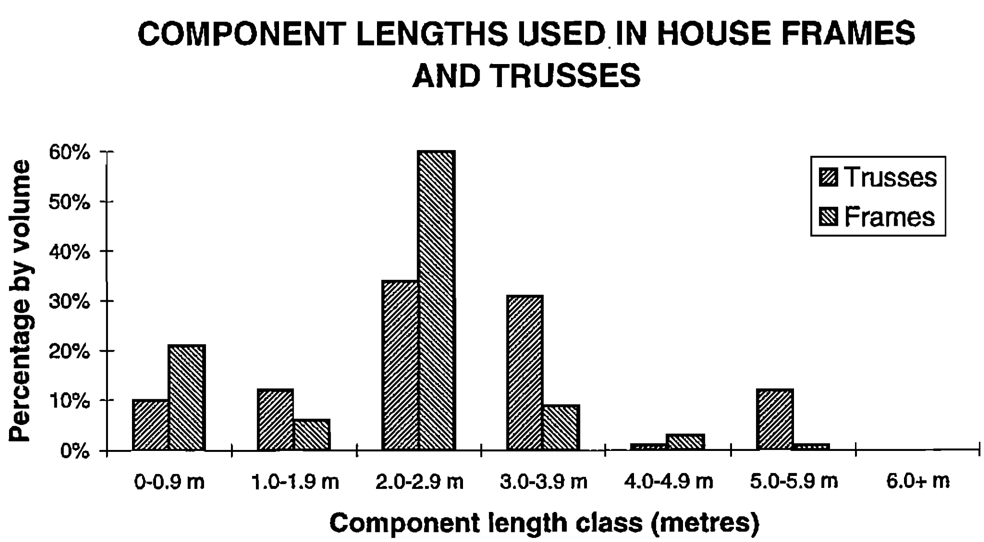
Figure 3



Source: Analysis of commercial cutting sheets by authors.

Typical lengths used in frame and truss components are given in Figure 4. The most popular length is for 2350 mm long studs. Components between 2000 and 2999 mm long account for over 50%, by volume, of all components used in house truss and frame construction.

Figure 4.



Source: Analysis of commercial cutting sheets by authors.

RESEARCH METHODOLOGY AND DATA

The research objective was to investigate the effect of packet length and grade on the number of trusses or frames that could be made.

For this study an "A" type truss of 7160 mm span with a spliced bottom-chord and 750 mm overhang at one end, was used to represent a domestic roof truss. The truss contained 25.4 linear metres of sawn timber, and the required componentry is given in Table 1.

Table 1. "STANDARD" TRUSS COMPONENTS

Component	Position	Number per truss	Actual Size mm x mm	Length mm
Top Chords	D-A	1	90 x 35 F5	3994
	D-G	1	90 x 35 F5	4732
Bottom Chords	K-A	1	90 x 35 F5	3760
	K-G	1	90 x 35 F5	3400
Webs	B-L & F-H	2	90 x 35 F5	566
	C-J & E-I	2	90 x 35 F5	1133
	L-C & H-E	2	90 x 35 F5	1369
	J-D & I-D	2	90 x 35 F5	1733

Source: Analysis of residential house truss cutting sheet by authors.

From the house frame data sheets analysed, the component requirements listed in Table 2 were identified as "typical" for house frames.

Table 2. "STANDARD" FRAME COMPONENTS

Component	Position	Number per frame	Actual Size mm x mm	Length mm
Plates	-Top	1	90 x 35 F5	4702
	-Bottom	1	90 x 35 F5	4732
Studs		8	90 x 35 F5	2350
Nogs	Normal	5	90 x 35 F5	565
	Right	2	90 x 35 F5	300
Jacks	Top	5	90 x 35 F5	85
	U Stud	2	90 x 35 F5	1975
	Sp Stud	2	90 x 35 F5	2105

Source: Analysis of residential house frame cutting sheet by authors.

The lumber for this study was obtained from two FRI sawing studies. One packet was obtained from thinnings and one packet from known clonal sources. The clones were selected to represent a wide range of log properties and the sawing patterns included both cant and Saw-Dry-Rip strategies which ensured a wide range of lumber qualities.

For this study only one lumber size was included in the evaluation. The truss and frame designs were limited to using only 90 mm x 35 mm lumber to keep analysis simple. In practice roof trusses may contain lumber components in two or three different widths. Normally the narrow widths are also short and used as webs. These web components are often obtained by ripping short lengths with the associated problem of having to re-grade the components after ripping. An alternative to ripping short lengths is to use a larger cross section in a lower grade. The frame contained only 90 mm x 35 mm components as the lintel over the window was excluded from the analysis.

As part of the study the graded lumber was sorted into different packets according to the criteria listed in Table 3. For the purpose of this study the lumber grades and prices listed in Table 3 were used.

Table 3. LUMBER GRADES AND PRICES

Lumber Grade	Nominal size mm x mm	Actual size mm x mm	Length m	Price* A$/lin m
KD, S4S, MSG F5+	100 x 40	90 x 35	Select 4.8 to 7.2 m	A$1.52 +5c/300mm over 6m
KD, S4S, MSG F5 +	100 x 40	90 x 35	Random	A$1.45
KD, S4S, MSG F4	100 x 40	90 x 35	Random	A$1.10
KD, S4S, MSG COL	100 x 40	90 x 35	Random	A$1.20

KD = Kiln dried; F5+ = F5 and better
S4S = Surfaced four sides; F4 = F4
MSG = Machine stress graded; COL = Cut of log

The prices are indicative, wholesale, delivered to Sydney yard, September 1996. Actual prices depends on many factors including order size and discounts.

DATA ANALYSIS

The research objective was to investigate the effect of packet length and grade on the number of trusses or frames that could be made. As it is possible to sort the available lumber according to a large number of criteria it was decided to analyse the data in the following stages in order to determine:

1. The number of "standard" roof trusses and house frames that can be cut from packets containing 100 pieces, 100 mm x 40 mm nominal, F5, kiln dried, select length lumber. The select lengths ranged from 4.8 to 7.2 metres in 300 mm increments. Average lumber consumption and lumber cost per truss and per frame was calculated.
2. The number of "standard" roof trusses and house frames that can be cut from the F5 and better component extracted from two Cut-Of-Log packets (A&B) of 100 mm x 40 mm nominal, kiln dried, random length, lumber.
3. The number of "standard" roof trusses and house frames that can be cut from the F4 and better component extracted from two Cut-Of-Log packets (A&B) of 100 mm x 40 mm nominal, kiln dried, random length, lumber.
4. The number of "standard" roof trusses and house frames that can be cut from two Cut-Of-Log packets of 100 mm x 40 mm nominal, kiln dried, random length, lumber.

The random length Cut-Of-Log packet, sample A, contained 160 pieces of lumber. The other packet, sample B, contained 100 pieces. Sample A was obtained from 16-18 year old thinnings with 85% 4.2 m long and an average length of 3.9 m. Sample B was obtained from 28 year old trees with 70% 5.1 m long and an average length of 4.8 m.

The cross cutting operation was optimised using a programme called PRECUT specially written for this purpose. The programme sorted the lumber and component order book according to a specified criteria and tried to make as many complete product units as possible, in this case roof trusses and house frames, from one full packet of lumber. Table 4 lists the results of the "standard" truss simulation runs with select lengths (Analysis 1).

Table 4. "STANDARD" TRUSS SIMULATION RESULTS

Packet Length (m)	Lumber supplied. (Linear metres)	No of trusses produced	Components produced (Linear metres)	Recovery (%)	Lumber cost per truss (A$/truss)
Select length 4.8 m F5	480	17	433.3	90.0	A$42.92
Select length 5.1 m F5	510	18	458.8	90.0	A$43.07
Select length 5.4 m F5	540	20	509.8	94.4	A$41.04
Select length 5.7 m F5	570	20	509.8	89.4	A$43.32
Select length 6.0 m F5	600	22	560.7	93.5	A$41.45
Select length 6.3 m F5	630	23	586.2	93.1	A$43.00
Select length 6.6 m F5	660	24	611.7	92.7	A$44.55
Select length 6.9 m F5	690	26	662.7	96.0	A$44.32
Select length 7.2 m F5	720	27	688.5	95.6	A$45.87

Table 5 lists the results of the "standard" frame simulation runs (Analysis 1).

Table 5. "STANDARD" FRAME SIMULATION RESULTS

Packet Length (m)	Lumber supplied. Linear metres	No of frames produced	Linear metres of components produced	Recovery %	Lumber cost per frame A$/frame
Select length 4.8 m F5	480	11	442.4	92.2	A$66.32
Select length 5.1 m F5	510	12	482.6	94.6	A$64.60
Select length 5.4 m F5	540	12	482.6	89.4	A$68.40
Select length 5.7 m F5	570	12	482.6	84.7	A$72.20
Select length 6.0 m F5	600	13	522.8	87.1	A$70.15
Select length 6.3 m F5	630	13	522.8	83.0	A$76.08
Select length 6.6 m F5	660	14	547.2	82.9	A$76.37
Select length 6.9 m F5	690	16	643.4	93.2	A$72.02
Select length 7.2 m F5	720	17	683.6	95.0	A$72.84

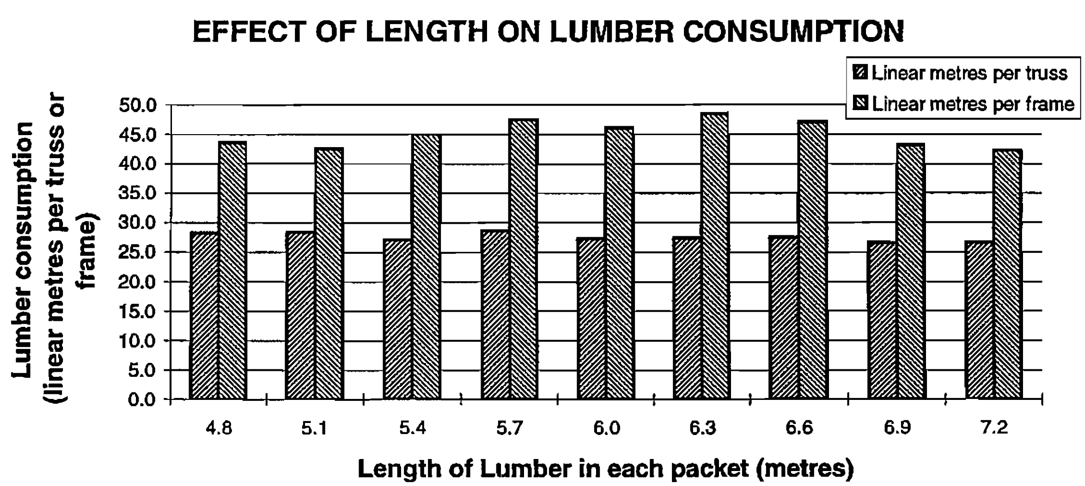
Table 6 lists the results of the "standard" truss and frame simulation runs using two qualities of random length lumber (Analysis 2,3 & 4). The random length Cut-of-Log packet, sample A, contained many shorts, and highlights the problem of short lengths often supplied in random length packets. Table 6 shows how variable the product yield can be when random length and Cut-of-Log lumber is used for truss and frame construction.

Table 6. "STANDARD" TRUSS AND FRAME SIMULATION RESULTS

Packet Quality Random length:	Lumber supplied. (Lin.m)	Number of trusses produced	Recovery %	Cost A$ per Truss	Number of frames produced	Recovery %	Cost A$ per Frame
F5+ Sample A	167	2	30.50%	A$ 121.08	4	96.30%	A$ 60.45
F5+ Sample B	372	14	95.90%	A$ 38.53	8	86.50%	A$ 67.43
F4+ Sample A	401	2	12.70%	A$ 249.78	4	40.10%	A$124.89
F4+ Sample B	484	17	89.40%	A$ 38.98	10	83.00%	A$ 66.26
COL Sample A	630	2	8.10%	A$ 378.00	4	25.50%	A$189.00
COL Sample B	511	17	84.80%	A$ 36.07	11	86.60%	A$ 55.75

Figure 5 shows the effect of purchasing packets of select lengths for the manufacture of frames and trusses. The lumber consumption indicates the linear metres of lumber supplied divided by the number of trusses or frames produced. The lumber consumption rate is based on producing an integer number of frames or trusses per packet. In practice the differences between length classes will be smaller than shown in Figure 5 because a large number of trusses are made from many packets of lumber. Figure 5 shows that 5.1 metres gives the lowest lumber consumption, from the standard range of select lengths, for trusses and 5.4 metres the lowest lumber consumption for frames. Figure 5 shows that very small recovery gains may be obtained by moving to select lengths over 6.3 metres, but the benefits of these recovery gains are usually lost due to the price premium charged for lengths over 6.0 metres.

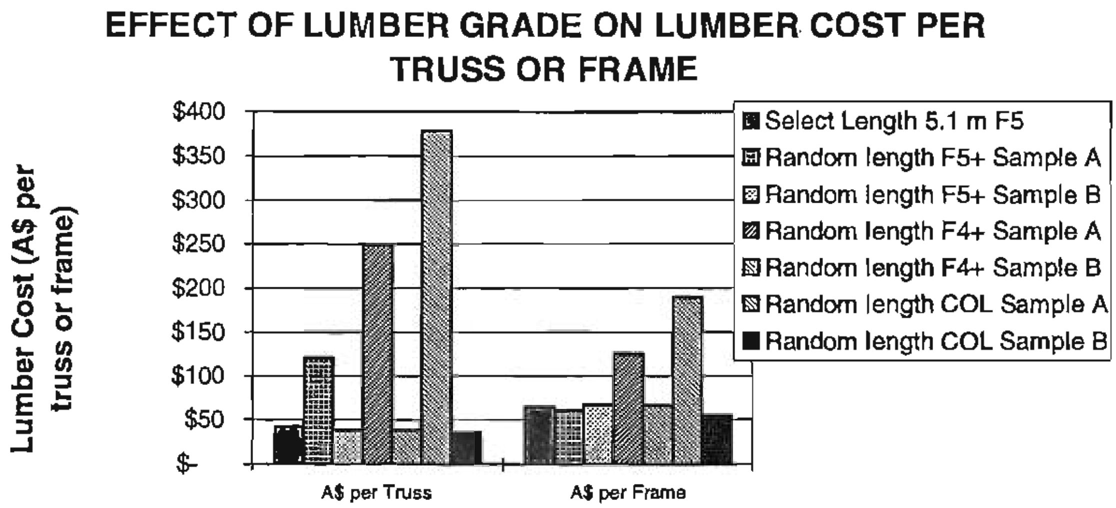
Figure 5.



One truss contains 25.4 linear metres of components
One frame contains 40.2 linear metres of components

With random length lumber, the lumber consumption depends largely on the packet length and grade mix. With a sample containing a good grade and length mix, results will be similar to select length. With a poor mix, consumption rates will increase. Figure 6 shows the effect of lumber grade on lumber costs per standard truss or frame. Lumber cost per truss or frame depends on the design, number of allowable splices, lumber lengths used and lumber grades available.

Figure 6.



Lumber Cost by Grade: Select and Random Length Packets

Figure 6 exaggerates the real situation as the shorter lengths can be spliced and offcuts can be on-sold. Figure 6 shows that the length mix and the quality of the lumber in random length and Cut-of-Log packets are very important. Unless reliable information is available on the exact length mix in a random length packet, or the exact component yield potential in a F4 or Cut-of-Log packet, grade sorted, select length, packets offer the least risk procurement option for a truss or frame manufacturer. If the correct lumber grade mix can be specified and supplied the cost per frame or truss can be reduced. The exact cost saving will depend on price differentials and grade yields. None of the grade combinations of sample A, shown in Table 6, appeared cost competitive for truss construction and only the F5 and better component appeared competitive for frame construction. All grade combinations from sample B were cost competitive for truss and frame construction and offered cost advantages over purchasing select lengths F5.

More work needs to be done to develop component yield grading rules to capture the benefits of improving the match between lumber grades and market needs. The solution to the problem can range from a component grading rule which guarantees, say a 90% yield in terms of a standard truss or frame, to cutting componentry to meet a custom orderbook.

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to investigate the potential benefits of an automated system to recover truss and house frame components from machine graded lumber. Analysis of the resource showed that the reduction in rotation age is shifting the grade mix to yield less F5 and better to more F4 lumber. Useable truss and frame components can be recovered from the lower grades but the economics of extracting F5 and better components from lower lumber grades depends on the length and quality of the lumber in each packet. If the correct lumber grade mix can be specified and supplied the cost per frame or truss can be reduced. The exact cost saving will depend on price differentials and component yields. The benefits obtainable by modifying truss and frame designs to suit the lumber grade mix recovered was not investigated but it was obvious that there are potential gains in having a better match between length and grade supply potential and customer needs.

During the study it became evident that some sawmillers have already moved into component production by withdrawing F4 as a commodity lumber and selling F4 only as cut to length components such as studs. The remaining shorts are grade sorted, finger-jointed, and remanufactured into products such as ceiling battens. An automated system to recover truss and house frame components from machine graded lumber can provide full width F4 components for webs, avoiding the use of ripped F5 as web components. This may also avoid the problem of regrading ripped machine graded lumber, a common industry practice.

The ability of an automated system to recover short length F8 components may also help to add flexibility to truss designs by, for example, eliminating the need for an increase in chord width to accommodate a cove ceiling. If component yield potential is to be introduced new delivery mechanisms and pricing policies will have to be developed, unless the component recovery process is done at the sawmills rather than at merchants. With the move to just-in-time, demand-pull production systems, some sawmills may find it is more economical to move into supplying pre-cut components rather than introduce component yield grading rules. The potential for component yield grading depends on the adoption of suitable machinery to relate stress graded lumber to component order files. It remains to be seen if component cutting stays with merchants or whether sawmills will move to offer a cutting service.

REFERENCES

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QUALITY OF STRUCTURAL PRODUCTS FROM *Rigidoporus* INFESTED LOGS

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ABSTRACT

Sawlogs salvaged from wildfires which swept the Beerburrum State Forest Plantations in September and November 1994, and then stored under water sprays, were intended to supplement the log intake to local sawmillers and to a plywood manufacturer over a period of up to five years.

The discovery of infestations of the white pocket rot fungus *Rigidoporus lineatus* changed these plans and the strategy adopted was to use the logs as quickly as possible before the extent of fungal degrade progressed beyond acceptable limits.

A program was initiated to monitor the production of both machine stress graded structural framing and structural plywood products and the results to date show that while the mechanical properties are different to that which would be expected from a freshly felled resource, the shift has not been significant enough to alter the structural 'F' grades assigned to the products.

INTRODUCTION

This report is part of an ongoing study to assess the mechanical properties of structural products manufactured from stored logs at the Beerburrum Storage Facility, to ensure structural adequacy and also to monitor the possibility of continuing deterioration associated with *R. lineatus* infestation in the resource.

METHOD

For the sawn timber study two packs of dry, rough sawn, sticks were selected at S and S Timbers, Gympie. The sticks were a random selection and were not graded prior to transportation (The only sticks which were not included in the sample were those which had excessive twist, spring and bow). The sample packs were transported to CSR Softwoods at Caboolture, where they were dressed to 70mm x 35mm and machine stress graded. The majority of the population was machine graded to F5, there was however a small number of sticks which were graded as F8. The sample was then transported to the QFRI Salisbury Research Centre, where an in-grade assessment of the population was carried out in accordance with AS/NZS 4063. Fifty-five of the sticks were chosen for in-grade bending and the remaining thirty sticks were set aside for in-grade tension testing.

For the monitoring of structural plywood, an initial sample of thirty sheets was selected, and tested in bending (parallel and perpendicular to grain) and in tension (parallel and perpendicular to grain), in accordance with AS/NZS 2098.9. This allowed for a benchmark of structural properties to be established, from which ongoing monitoring could progress. Following the initial testing, three subsequent weekly monitoring trials were carried out in which ten sheets were selected in the same manner as the initial selection, and the results of these smaller trials were added to the initial sampling results to try to ascertain any shift in the properties of the material.

The sheets selected for testing were 2400 mm x 1200 mm 12-24-5 (12mm thickness - with a make-up of five 2.4mm veneers) in accordance with Table 3.1 of AS/NZS 2269 visually graded to F14. A random pack of sheets from the log storage resource was selected and all sheets in the pack were proof graded to F17 by staff at Boral Hancock's Plywood manufacturing facility in Ipswich. For the initial sample, thirty sheets were selected, being those that showed the worst visual or audible signs of distress under the applied load. For monitoring trials, sheets were selected in the same manner.

Test pieces were cut from the panels according to the cutting pattern illustrated in Figure 1 of AS/NZS 2098.9. Compression and panel shear tests were not included in the testing schedule, on the advice of the Plywood Association of Australia that bending and tension properties would be adequate to establish and monitor structural adequacy of the panels.

Testing of the pieces was carried out at the Queensland University of Technology. Bending samples were tested for both stiffness (modulus of elasticity) and strength (modulus of rupture), while tension samples were tested for strength only.

RESULTS AND DISCUSSION

Sawn Timber

Table 1 below summarises results from the in-grade study of sawn timber. At the time of writing, results for in-grade bending tests only were available: Reassessment of results will be carried out when tension test results become available.

Table 1 : In-Grade Testing Results for Sawn Timber

Stiffness		Strength	
E_{mean}	13444	R_{mean}	58
$E_{st.dev}$	2879	$R_{st.dev.}$	22
E_{CofV}	0.21	R_{CofV}	0.37
$E_{0.05}$	8741	$R_{0.05}$	21
		R_k	18
E_k	**12089 MPa**	**R_{basic}**	**7 MPa**

By comparison with the above, results quoted from Hyne and Sons, on their participation in a Pine Australia in-grade study of 90 x 35 F5 machine stress graded slash pine from Tuan resource are indicated in Table 2 below:

Table 2: In-Grade Results from Pine Australia Slash Pine Study

Stiffness		Strength	
E_{mean}	10400	R_{mean}	51.8
E_{CofV}	0.12	R_{CofV}	0.23
$E_{0.05}$	7100	$R_{0.05}$	22.8
		R_k	21.2
E_k	**10254**	**R_{basic}**	**8.3**

The above comparison indicates that there is no significance (p=0.1) between the MOR of sawn sections from the log storage facility and that of fresh felled logs. At the same confidence level (p=0.1) however, there is a significant difference between the MOE of log storage material, as compared with fresh felled material - the log storage material having higher MOE. It should be noted in the comparison of the above two populations, the statistical significance which occurred for the MOE may be due to the fact that the material was cut and dried for an appearance grade product, and thus knots and other defect which would have been present in the Pine Australia results may not have been as prominent in the Log Storage Facility study. The difference in sawn size of the two populations, as well as the location of the resource may also have been contributing factors in the difference in results. A regression analysis was carried out on the relationship between MOE and MOR for both populations. The relationships for the Log Storage Facility and the Pine Australia study respectively are indicated below:

Log Storage **MOE (GPa) = 7.746 + 0.98 x MOR (MPa)**

$\therefore R^2 = 0.533$

(Relationship based on 70 x 35 F5 and F8 MSG slash pine from log storage facility)

Pine Australia **MOE (GPa) = 7.999 + 0.93 x MOR (MPa)**

$\therefore R^2 = 0.489$

(Relationship based on 90 x 35 F5 and F11 slash pine from Tuan resource)

The above would suggest that there is little shift in the E/F_b relationship for the log storage facility resource. This is important as grading of this resource will be achieved by machine stress grading, and the above suggests that current machine settings for slash pine can be used for the grading of the log storage resource.

In comparison of the two populations, it is noted that the coefficients of variation for both stiffness and strength in the log storage resource are higher than for the Pine Australia study. This would indicate that while the shift in mechanical properties is not significant in the assigning of a stress grade to the population, there is more variability in the properties within the population.

Plywood

For the in-grade testing of plywood from the log storage resource, Table 3 below summarises the characteristic stiffness in bending, and the basic permissible stress in both bending and tension, obtained from a statistical analysis of the sample in accordance with AS/NZS 4063.

Table 3 : In-Grade Results for Initial Plywood Study

Test Pieces Parallel to Face Grain					
E_{mean}	13919	R_{mean}	71	T_{mean}	40
$E_{st.dev}$	2413	$R_{st.dev}$	19	$T_{st.dev}$	9
E_{CofV}	0.17	R_{CofV}	0.26	R_{CofV}	0.23
$E_{0.05}$	9115	$R_{0.05}$	41	$T_{0.05}$	27
		R_k	35	T_k	23
$\mathbf{E_{basic}}$	**12505**	$\mathbf{R_{basic}}$	**14**	$\mathbf{T_{basic}}$	**9**

Test Pieces Perpendicular to Face Grain					
E_{mean}	13976	R_{mean}	86	T_{mean}	49
$E_{st.dev}$	2458	$R_{st.dev}$	28	$T_{st.dev}$	14
E_{CofV}	0.18	R_{CofV}	0.32	R_{CofV}	0.28
$E_{0.05}$	10096	$R_{0.05}$	48	$T_{0.05}$	29
		R_k	40	T_k	25
$\mathbf{E_{basic}}$	**13662**	$\mathbf{R_{basic}}$	**15**	$\mathbf{T_{basic}}$	**10**

From Table 4.2 in AS/NZS 2269, the stress grade which can be applied to the population based on the above results is F14. This is consistent with the grading which is assigned to plywood from similar freshly felled logs. There is however a shift in the E/F_b relationship, which was discovered in the initial proof grading to obtain the sample population. The stress grading machine used at Boral Hancocks can be operated in two modes. Mode 1 sorts on the basis of stiffness only, and Mode 2 applies a proof load of 1.25 x F_b. For sound wood, the stiffness criteria is in most cases the limiting factor for the assignment of the stress grade, so the 25% increase in the proof load above the basic working stress does not cause problems as the strength of the material is higher than that required to pass as F14 structural. However, in the case of plywood from the log storage resource, visible and audible cracking was occurring when some sheets were proof loaded above the basic working stress. This indicates that while the storage resource is making grade in accordance with in-grade testing procedures and minimum strength and stiffness criteria set out in AS/NZS 2269, the strength of the material is less than the strength of equivalent F14 graded plywood from freshly felled logs.

Tables 4 to 7 show in-grade results of initial testing, combined with on-going monitoring results. These on-going tests indicate that there is minimal shift in the mechanical properties of the plywood, and that the assigning of an F14 stress grade to the population is justified.

As for the sawn timber study, it is again noteworthy that the coefficients of variation for both stiffness and strength of the plywood are higher than what would be expected. This is again an indication that while the shift in mechanical properties has minimal effect on the assigning of a stress grade, the variation within the population is greater than what would be expected from plywood produced from a freshly felled resource.

Table 4 : In-Grade Results for Monitoring of Plywood (Combined Initial Testing with First Monitoring Trial)

Test Pieces Parallel to Face Grain					
E_{mean}	13865	R_{mean}	69	T_{mean}	40
$E_{st.dev}$	2235	$R_{st.dev}$	19	$T_{st.dev}$	9
E_{CofV}	0.16	R_{CofV}	0.28	R_{CofV}	0.22
$E_{0.05}$	9203	$R_{0.05}$	41	$T_{0.05}$	26
		R_k	36	T_k	24
E_{basic}	**12843**	R_{basic}	**14**	T_{basic}	**9.4**

Test Pieces Perpendicular to Face Grain					
E_{mean}	14109	R_{mean}	84	T_{mean}	48
$E_{st.dev}$	2198	$R_{st.dev}$	27	$T_{st.dev}$	14
E_{CofV}	0.16	R_{CofV}	0.32	R_{CofV}	0.28
$E_{0.05}$	10112	$R_{0.05}$	44	$T_{0.05}$	25
		R_k	38	T_k	22
E_{basic}	**13865**	R_{basic}	**14**	T_{basic}	**8.5**

Table 5: In-Grade Results for Monitoring of Plywood (Combined Initial Testing with First and Second Monitoring Trial)

Test Pieces Parallel to Face Grain					
E_{mean}	13517	R_{mean}	67	T_{mean}	40
$E_{st.dev}$	2242	$R_{st.dev}$	18	$T_{st.dev}$	9
E_{CofV}	0.17	R_{CofV}	0.27	R_{CofV}	0.22
$E_{0.05}$	9093	$R_{0.05}$	41	$T_{0.05}$	26
		R_k	37	T_k	24
E_{basic}	**12800**	R_{basic}	**14**	T_{basic}	**9.4**

Test Pieces Perpendicular to Face Grain					
E_{mean}	13436	R_{mean}	83	T_{mean}	48
$E_{st.dev}$	2263	$R_{st.dev}$	24	$T_{st.dev}$	14
E_{CofV}	0.17	R_{CofV}	0.28	R_{CofV}	0.28
$E_{0.05}$	10105	$R_{0.05}$	48	$T_{0.05}$	25
		R_k	43	T_k	22
E_{basic}	**13223**	R_{basic}	**17**	T_{basic}	**8.5**

Table 6: In-Grade Results for Monitoring of Plywood (Combined Initial Testing with First and Second and Third Monitoring Trial)

Test Pieces Parallel to Face Grain					
E_{mean}	13675	R_{mean}	68	T_{mean}	40
$E_{st.dev}$	2216	$R_{st.dev}$	18	$T_{st.dev}$	9
E_{CofV}	0.16	R_{CofV}	0.27	R_{CofV}	0.22
$E_{0.05}$	9131	$R_{0.05}$	42	$T_{0.05}$	26
		R_k	38	T_k	24
E_{basic}	**12942**	R_{basic}	**14**	T_{basic}	**9.4**

Test Pieces Perpendicular to Face Grain					
E_{mean}	13453	R_{mean}	81	T_{mean}	48
$E_{st.dev}$	2230	$R_{st.dev}$	25	$T_{st.dev}$	14
E_{CofV}	0.17	R_{CofV}	0.30	R_{CofV}	0.28
$E_{0.05}$	10093	$R_{0.05}$	41	$T_{0.05}$	25
		R_k	37	T_k	22
E_{basic}	**13259**	R_{basic}	**17**	T_{basic}	**8.5**

CONCLUSION

For both the structural sawn timber and the structural plywood, the invasion of the log storage facility resource by *Rigidoporus lineatus* has caused a change in mechanical properties from what would be expected from a fresh felled resource. The statistical analysis of samples from the population undertaken in accordance with AS/NZS 4063 indicates that while the properties have changed, they have not been altered to the point that their structural 'F' grade would be lowered.

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FWPRDC DURABILITY DESIGN PROJECT SUB-PROGRAM 2: ENVIRONMENTAL HAZARDS AND MAPPING

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ABSTRACT

Sub-program 2 of the FWPRDC durability design project focuses on environmental hazards and mapping. Within this framework, three types of timber degradation are considered: termite attack, fungal attack and joint degradation. These three areas form three of the sub-projects. In addition, a sub-project focuses on the microclimate in Australian houses. This paper outlines progress to date in each of these sub-projects. It discusses different approaches to mapping with particular emphasis on a parametric approach. In this context, data is analysed to assess the accuracy of Scheffer's Index as a parameter for predicting decay. It is found that Scheffer's Index only partially explains the observed site-to-site variation in decay. A discussion of other possible parameters defining fungal decay and joint degradation is presented.

INTRODUCTION

The environmental hazards and mapping project aims to establish a system to define the risk of degradation of a timber structure as a function of its geographic position and type of use. The forms of degradation are restricted to:

- termite attack;
- fungal attack; and
- joint degradation.

The aim is to construct a system applicable to all of Australia and capable of producing assessments of risk which can be used in life prediction models. Thus it is desirable to develop parameters that define the probability, degree and rate of attack as a function of geographic and climatic zone. Depending on the degradation mechanism, different methodologies may be used to derive such parameters.

Two approaches are commonly used in developing maps and criteria. The first is to define the magnitude of the hazard level based on laboratory or test site measurements, and then by some process divide the area to be mapped into these hazard levels (hazard level approach). In the second approach, the performance is defined as a function of climatic or other parameters and then these parameters are mapped for the geographic space (parametric approach). In fact often these approaches merge. For example, Scheffer's Index is often used to correlate against above-ground performance, with geographic distribution of hazard levels being based on Scheffer's Index. Thus researchers or practitioners assume that the above-ground durability performance of a timber in an area of north Queensland which has a Scheffer's Index of 140 will be the same as in a test site having the same Scheffer's Index. This process is implicitly stating that durability depends on rainfall and temperature which can then be readily mapped. One aim of this sub-program is to assess to what extent the degradation processes can be related to factors that are readily mappable.

Consider the corrosion of metal connectors in timber. This degradation mechanism is a simpler case than either termite or fungal attack and thus can serve as a simple illustration of how the parametric approach may work. It is established that corrosion, including corrosion of nails in timber, is an electrochemical phenomena. For corrosion to occur there are two main requirements: a potential difference must be established, and there must be a conductive path between the cathode and anode. In the case of a nail in timber, it is useful to separate corrosion into head and shank corrosion. Considering shank corrosion, the oxygen difference down the shaft of the nail sets up a potential difference, while current flow will depend on the resistance between the anode and cathode and thus on the conductivity of the wood or wood/metal interface. The conductivity will in turn be related to moisture content or water potential of the wood and the free ions present in the timber. It will thus depend on equilibrium moisture content (EMC) or water potential, timber type and chemical treatment. It should thus be possible to develop relationships between timber moisture content, timber type and connector corrosion. If these relationships are general they should hold for all service conditions, so if the variation in timber EMC over the life of a structure can be predicted, then the corrosion rate of the fasteners should be predictable. EMC should in turn be able to be estimated on the basis of climatic parameters.

Extensive research is being undertaken, within the program, to define the microclimate within domestic buildings as a function of building design and geographic and corrosion location. Thus, at least in the case of connector corrosion, it is hoped that basic components defining the degradation phenomena can be defined and related to an aspect of timber condition which in turn can be related to microclimatic variables. It is hoped that such microclimatic variables can be predicted on a national basis. In the case of fungal and termite risk, the approach may not be so simple as the basic components defining the degradation are more complex and their relation to timber condition less certain. In this case, a mixed hazard level and parametric approach may be required.

DETAILS OF THE SUB-PROGRAM

The sub-program has five component projects:

- microclimate;
- corrosion;
- termites;
- above-ground decay; and
- in-ground decay.

Although each of the projects functions separately, they are or will be coordinated both at the practical (selection of sites/timbers etc.) and at the theoretical level (where possible adopting the same form of degradation models). At this stage of the program, coordination is primarily on the practical level with, for example, sites being coordinated and matched as indicated in Table 1. The sites in bold are the critical common sites which have been chosen to cover the major climate zones of importance, viz:

- Innisfail – wet tropics;
- Brisbane – subtropics;
- Sydney – warm temperate;
- Melbourne – temperate; and
- Narrandera – inland.

MICROCLIMATE STUDIES

Aims and Experimental Procedures

The microclimate studies aim to determine the microclimate, and the response of timber and connectors to this microclimate, in a range of houses that can represent conditions in at least eastern Australia if not all of Australia. The results from some of these studies are being reported more fully in a technical paper being given by Cole *et al.* (1996)

TABLE 1
COMMON SITES

Sites	Above-ground	In-ground	Deck above	Corrosion	Micro-climate	Engineered joints
Innisfail	•	•	•	•	•	•
Townsville		•				
Beerburrum/Brisbane	•	•	•	•	•	•
Sydney	•			•	•	
Melbourne	•	•	•	•	•	•
Narrandera		•	•	•	•	•
Walpeup	•	•				
Mt Buller			•	•		
Taree		•				

at this conference. Depending on the type of house, the conditions of the house exterior, two areas of the subfloor, at least one wall cavity and the roof space are being monitored. Subfloor areas which are in the path of cross-flow ventilation as well as areas in which ventilation is restricted are being monitored. Two types of sites are being established: heavily monitored sites; and lightly monitored sites.

In the heavily monitored sites, relative humidity (RH) and temperature are measured at each location (except roof space for some houses) and stocks of a range of timbers are placed at each location. Species include radiata pine, CCA-treated radiata pine, Douglas fir, mountain ash, brush box and spotted gum. Test specimens have no finish coatings and have the dimensions 35 mm wide × 20 mm deep × 200 mm long. The sticks are weighed each season. Further, continuous electronic monitoring of the existing structure is being undertaken of beams, joists and floorboards in a well-ventilated and restricted area of the subfloor, as well as of the bottom plates in the wall cavity. Lastly EMC measurements will be made at each seasonal visit using a hand-held meter, and rainfall is monitored continuously. In the lightly instrumented sites, RH and temperature measurements in the normal and restricted subfloor and in at least one wall cavity, as well as the continuous electronic EMC measurement of the existing structure, are undertaken.

In the whole program, work has focused on a number of sites as detailed above. The microclimate study includes the five common sites but also incorporates Mt Buller. Mt Buller represents a cold climate site where condensation-induced moisture was considered likely to be a considerable problem. Mt Buller should be representative not only of mountainous mainland regions but of conditions in parts of Tasmania and in Australian subantarctic and antarctic territories. The matrix of houses to be monitored is given in Table 2. Those in bold are already established. As is evident from the table, the aim is to establish a range of house construction types with varying degrees of ventilation.

Initial Results

Results of two types are obtained from the studies: microclimate measurements; and timber response.

Microclimate measurements as detailed above include RH and temperature of various building envelope spaces. These are important in themselves but can also be used to calculate estimated EMC and surface EMC within timbers. Timber response measurements include site EMC measurements on in-situ timbers and timber sticks,

TABLE 2
MATRIX OF HOUSES TO BE MONITORED

Innisfail	Brisbane	Sydney	Melbourne	Narrandera	Mt Buller
BV, sloped ground	**BV, sloped ground**	**Brick clad, restricted vent.**	**Solid brick**		**block, built into hill**
Queenslander, good vent., W	BV, good vent.	BV, good vent.	BV, good vent.	**BV, good vent.**	
W, poor vent.	W, good vent.	W, good vent.	W, good vent.	W, good vent.	
BV, poor vent.	BV, poor vent.	BV, severe marine	BV, poor vent.	BV, poor vent.	

BV = brick veneer; W = weatherboard; vent. = ventilation.

continuous electronic EMC measurement on in-situ timber, and weight changes of timber sticks. In general, indications are that all the methods are relatively consistent, although the surface EMC measurements are higher and more variable than all the other measurements which consider internal EMC. Major surprises have been that estimated EMC, in particular, is higher than anticipated (for a full discussion see Cole *et al.* (1996)). This is particularly the case in wall cavities and poorly ventilated subfloors. In most of these cases, surface EMC values do not exceed 24% and thus initiation of wood decay fungi is unlikely, however growth of pre-existing fungi or deterioration of moisture-sensitive glues is possible. Under severe conditions associated with high rainfall and restricted ventilation (Innisfail) or design features causing dead air pockets (Sydney), surface EMC values could be as high as 30%. In fact, at Sydney wood decay fungi has commenced growing on all sample sticks, except CCA-treated pine, which have been under the floor in the area of dead air for only six months.

Future Work

At the completion of the project, the microclimate and timber response will be known in 20 houses with varying construction types and ventilation rates. In addition, data from another 15 houses (all slab on ground) will be available from previous surveys, giving a total database of 35 houses. Models of the interaction of exterior climate and building type will then be established from these 35 houses which will permit an estimate of the microclimate and timber response for major Australian housing types in most Australian climatic zones. This database will then link with the hazard work for the various degradation modes, and if such degradation modes depend on microclimate, the hazard in any position of a given house in a given position can then be determined.

CORROSION STUDIES

As outlined in the introduction, the area of corrosion is the one where a parametric approach is most likely to succeed. Initial results have aimed at defining what parameters may control corrosion of connectors in timber. Initial studies were carried out in modified salt spray test chambers. In these tests, neutral 5% NaCl was sprayed continuously for 100 hours over nail boards fabricated from the same five types of timber and having the same dimensions as in the microclimate exposures. The test specimens were 35 mm wide

× 20 mm deep × 200 mm long. Each piece had the ends sealed with epoxy resin which was cured before assembly. There were four types of commonly available nails used in the test: 41 mm long hot dipped galvanised; 31 mm long zinc plated; 40 mm long blue processed; and 30 mm long uncoated bright nails. Processed nails are bright nails covered with a light polymeric film. The test specimens were constructed by nailing two pieces of each wood along its length on the 35 mm flat with three samples of each type of nail. The separation between each nail was at least 15 mm, allowing 12 nails per wood type, arranged in two offset lines.

The tests showed that the head corrosion of the nails was virtually independent of the wood type and thus also of the EMC within the timber. On the other hand, there was a strong dependence on shank corrosion with wood type. In fact, on the basis of the salt spray test, the weight loss (in grams per metre square of shank) results could be divided into five classifications: severe (>200 g/m^2); high (100–200 g/m^2); moderate (30–100 g/m^2); low (10–30 g/m^2); and negligible (<10 g/m^2). Note that these classifications do not necessarily correlate with serviceability after testing, for example hot dipped nails, although suffering the fastest corrosion rate, remain the most serviceable as they are free from red rust. In Table 3 a matrix of nail/timber is given with the appropriate classification.

However, during the test the timbers reached different EMC values as defined in Table 4. Thus, it is unclear whether the differentiation reflects the difference in timber or in EMC values.

Future Work

Traditional work is being undertaken to determine the corrosion rate as a function of EMC for the different woods. In these tests, timbers are being conditioned in a range of chambers to induce constant EMC. Each salt chamber is at a constant humidity and

TABLE 3
WEIGHT LOSS RATINGS

Timber	Bright	Hot dipped	Processed	Zinc plated
CCA-treated radiata pine	High	Severe	High	Moderate
Radiata pine	Moderate	High	Moderate	Moderate
Douglas fir	Moderate	Severe	Moderate	Moderate
Brush box	Low	Low	Low	Low
Spotted gum	Low	Low	Low	Negligible

TABLE 4
EMC AFTER SALT SPRAY TEST

Timber	Approximate EMC after test (%)	Time to dry (days)
CCA-treated radiate pine	64	8
Radiata pine	41	7
Douglas fir	24	10
Brush box	13.5	9
Spotted gum	14.5	10

temperature in order to produce surface EMC values of 18, 20 and 25%. Once the timbers reach constant weight, nail boards will be made and placed back in the chambers. Timbers under study include CCA-treated pine (grade 2), low organic solvent preservation (LOSP) treated pine (grade 2), radiata pine, Douglas fir, brush box, spotted gum, mountain ash, huon pine, karri, kauri, red iron bark, meranti and plywood. It is noteable that as EMC is a function of the mass of the timber, the actual water content of different timbers may differ at constant EMC values. Thus, a dense hardwood may have by weight significantly more moisture content than a softwood. Degradation, either physical or biological, may depend of the actual amount of free water rather than the per cent weight. Thus, it is possible that EMC may not be the most valid measure for cross-comparisons of timber performance. An alternative parameter, which some workers have found to correlate better with at least some aspects of decay, is water potential. This further work will assess which is the most valid parameter for predicting corrosion rate in timber.

TERMITE ATTACK

The first stage in developing a hazard map for termites is to undertake a national risk survey covering all states and territories of Australia. This survey has been undertaken in collaboration with the CSIRO Double Helix Club. Each student has been asked to survey up to 20 houses at random (not necessarily those that contain termites). Students have been provided with a questionnaire that gives details of type and features of the house and gardens as well as locations of termites. Over 10,000 schools have been involved and it is estimated that up to 20,000 houses will be surveyed. To date 1000 houses have been surveyed and 34% had termites.

As it incorporates both houses with and without termites, the advantage of this type of survey is that it will give an accurate estimation of the risk of termite attack, as well as a complete database which will allow an assessment of factors both geographic and local (house design, garden features etc.) that increase the risk of attack.

ABOVE–GROUND DECAY

The above-ground decay project is making use of existing data as well as establishing limited additional exposures. Two types of trials have been undertaken: CSIRO climate index tests; and Queensland–DPI L-joint test. CSIRO has recently terminated its long-term climate index test, while a new targeted set of restricted species over a shorter time span has commenced with the distribution of specimens to 27 sites. These sites include the common sites listed above and in full are: Taree; Narrandera; Brisbane (Salisbury); Beerburrum; Dalby; Mackay; Innisfail; Sydney (Pennant Hills); Dubbo; Batlow; Canberra; Melbourne (Highett, Rowville and Carrum); Creswick; Horsham; Powelltown; Hobart; Walpeup; Mt Gambier; Wirrabara; Adelaide; Katherine; Beerburrum; Perth; Narrogin; Manjimup; and Port Hedland. Five panels each of radiata pine sapwood and mountain ash heartwood are being set out at each site. The sidesof the panels are painted with a coat of primer, followed by two coats of white water-based Dulux, while end grains are not sealed. The old CSIRO climate test was carried out for a total of 15 years exposure at most of the 27 sites listed above. Final inspection and data gathering has been made within this program. Soft rot appears to be the most frequent decay type at all sites.

The QLD–DPI has established above-ground durability tests of L-joints (painted and unpainted) at 11 sites. Nine timber types (one of them CCA-treated) and 18 replicates were used. In addition, a main site at Beerburrum has an additional 27 timber types under test. The set-out was established outside of this project while analysis of the seven- and nine-year data is being undertaken within this project. In addition, within Sub-program 3b a new set-up of painted and unpainted joints is being established at the first five sites given in Table 1.

Initial Results

The seven-year L-joint data has been analysed and regression analysis carried out against Scheffer's wood decay index for each site (based on 75 years of climate data). Assuming a linear model, an r-squared value of 0.70 is obtained, while if a non-linear logarithmic curve is used, an r-squared value of 0.77 is obtained. Thus, Scheffer's Index does explain a substantial part of the variation in decay, however, it is notable that decay scores of one value may cover a substantial range in Scheffer's Index. Thus, although Canberra, Rockhampton, Townsville and Hay Point all have approximately the same decay score, their Scheffer's Index values range from 44 to 114. In a similar way Beerburrum and Hay Point have Scheffer's Index values of 116 and 114 respectively, but have decay scores of 2.13 and 2.85 respectively.

The CSIRO climate index for decay above ground is based on an 8-point rating of panels of 10 different timbers. Ratings of remaining panels are summed at the completion of the 15-year test period. A number of sites had very low ratings indicating substantial decay. Low ratings occurred for sites with both high (Mackay, Innisfail, Katherine) and medium or low (Dubbo, Batlow, Highett) Scheffer's Index values. Thus, these studies confirm the conclusion from the L-joint work that Scheffer's Index can only partially account for the variation in above-ground decay.

Some of the lack of fit between decay indices and Scheffer's Index may arise from experimental procedures. The decay evaluation assigns an integer value on a restricted scale. Thus, given that the scales are non-continuous, a high degree of fit with any index is not possible. However, even given this sampling limit and possible random causes of error, it must be concluded that factors in addition to rainfall and temperature may be controlling decay.

IN-GROUND DECAY

Five radiata sapwood samples (treated with insect repellent) have been set out at each of the 27 sites listed above. Results from existing CSIRO tests are being analysed within Sub-program 3b and will feed into this program.

DISCUSSION

As Scheffer's Index appears to not fully explain the observed site-to-site variation in above-ground decay, the program will investigate other parameters. Guidelines in this determination may come from a fundamental understanding of the relationships between timber structure, moisture and decay. Griffin (1977) presents a clear summary of the relationship between voids and moisture in wood. According to Griffin, wood voids fall into three categories according to their dimension. Large voids with radii of 5–200 μm are formed by laminas of cells. Medium size voids are formed by features such as pit apertures and pit membrane pores and have dimensions of 0.01–5 μm. Lastly, swelling of cell walls forms small transient voids of dimensions less than 0.01 μm. At a relative vapour pressure of 1 or water potential of 0 bar, all the voids will be filled. As the water potential falls from 0, desorption occurs and leads to the drainage of the major voids which is complete at –0.3 bar, then drainage of the secondary voids down to –140 bar (or relative vapour pressure of 0.9), and lastly drainage of the transient voids at less than –140 bar. Griffin goes on to discuss the conditions required for fungal growth. He argues that the structure must contain water in such a way as to permit the diffusion of both the enzymes or other metabolic catalysts of the decay fungi and the partial degradation products from which they derive their nourishment. Thus, decay can occur when the cell laminas contain water and will persist as long as the larger voids of the second type contain water, but will cease when these larger voids are empty (at a water potential of around –40 bar). Thus, the analysis of Griffin proposes that fungal growth is indeed limited by the physical property of water potential. In principle, water potential can be related to microclimatic properties, although the exact form of the relationship is unclear. It may be appropriate to estimate water potential from partial vapour pressure or EMC for given timber types, or it may be more direct to bypass these parameters and go directly to climatic parameters such as RH, temperature and rainfall.

The analysis of Griffin may also be of relevance to corrosion studies. As indicated in the introduction, what is critical to shank corrosion is the resistance between the cathode and anode. This will depend on the path length and the resistance along that path length. Clearly if cell laminas are full, highly conductive paths will occur. As cells drain, the path length will progressively increase. However, unlike the case of fungal decay, even water-filled voids of the smallest type may contribute to a path of increased conductivity with respect to that in dry wood. Thus, a single critical limit for corrosion may not occur, rather there may be a progressive decrease in corrosion as the water potential is lowered. However, as with fungal growth, the distribution of water rather than the total weight of water in the timber is most likely to be crucial.

Regardless of whether the critical parameters controlling fungal decay and corrosion are water potential or EMC or other related physical factors, models relating this parameter to environmental conditions must be derived. In order to predict the moisture within a piece of timber, a model of conditions at the surface must be developed. Two aspects must be analysed: deposition and evaporation of bulk water (rain or condensation); and the equilibrium established between humid air and the timber surface EMC. The first aspect may be treated by standard thermodynamics. In fact, Cole and Holgate (1995) have developed such an approach for metal surfaces, while the work of Bramhall (1979) provides the basis for the second. Advances in computing and increased access to meteorological data render it possible to calculate moisture condition from hourly or three-hourly meteorological data given that an appropriate model is developed.

The challenge of this project is to bring all the aspects discussed in this paper together. As discussed above, there is a strong theoretical basis for assuming that a parametric approach to risk mapping may be effective for fungal decay and corrosion, while in the case of termites the traditional hazard level approach may well be the most effective.

CONCLUSIONS

The research program is in its first of four years and thus much of the work to date is preparatory. Thus, at this stage it is not appropriate to develop technical conclusions. What should be emphasised is that a systematic program has been established in order to develop a reliable design methodology for durable timber structures. Within this framework, systematic and coordinated work is being undertaken to define, on a national basis, the hazards and risk of timber degradation as a result of termite attack, fungal decay and joint degradation.

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STRUCTURAL TESTING OF ARAUCARIA CUNNINGHAMII AND THE APPLICATION OF RESULTS TO A COMMERCIAL TIMBER OPERATION

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ABSTRACT

In recent years two studies on the full size structural properties of Araucaria cunninghamii have been undertaken. This report summarises some of the results from these studies and indicates how the results were used to develop new grading rules and machine settings for the commercial production of structural timber at Hyne and Son's Melawondi and Imbil sawmills. In 1993 Hyne and Son tested 190 x 35 sections in bending and determined that AS2858 grading rules where inaccurate. In 1995 ACI Timber Products and Hyne & Son, through TRADAC, sponsored a study, into the structural properties of 140 x 35 and 240 x 45 sections. This study concluded that AS2858 was ineffective at sorting this timber. Simple visual grading rules based on the evaluation of one or more knot types has the potential to provide a more effective grade sort. Mechanical stress grading is also a valid grading method for this timber. A multitude of timber grading options can be determined from the results of the studies undertaken. AS2858 should be amended to correct current deficiencies and provide a means of endorsing the range of potential visual grading options available to producers. The structural properties of Araucaria cunninghamii products are now more accurately known and thus more reliable.

INTRODUCTION

ARAKARIA™ is a registered trade name owned by Hyne and Son, and used to identify wood products, produced from Queensland's Araucaria cunninghamii plantation resource. ARAKARIA™ is now the most common name for this species in the timber marketplace, replacing the older name of Hoop Pine. Knots in this timber generally occur in pronounced whorls at intervals varying from 300 mm to 2500 mm with very clear even coloured wood in between. The clear wood is recovered between knots to produce premium furniture components, joinery and mouldings. Timber which has knots at relatively close centres or which contains natural defects that may detract from its appearance, is graded for use in structural products.

AS 2858-1986 "Timber - Softwood - Visually Stress-Graded for Structural Purposes" provides the current basis for visual stress grading of ARAKARIA™. The grading rules in this standard and the method of assigning structural properties evolved from a theoretical grading system developed by CSIRO in the 1960's. This system was based on the testing of small clear pieces of timber. AS2858 currently allows this wood to be assigned stress grades from F7 to F17 in a seasoned condition and from F4 to F8 in an unseasoned condition. Full size structural testing on Cypress (Callitris glaucophylla) and some North American softwood species has indicated that the theoretical structural properties predicted by the CSIRO strength group/structural grade system may not be achieved. This necessitated that the system be "unlocked" for these species. eg. Cypress can only be visually graded to F4, F5 and F7 with no reference to a strength group.

Some full size testing undertaken during the development of proof grading technology suggested that knot whorls in Araucaria cunninghamii could severely limit the achievement of high bending strengths in this species. In 1993, Hyne and Son decided to introduce a structural Hoop pine product. The potential inadequacies of AS2858 were recognised by Hyne and Son who commissioned a study to investigate the "real" structural properties of ARAKARIA™ (Stringer 1993). In 1995, as a result of this study a more detailed collaborative study was pursued by Hyne and Son and ACI Timber Products, through TRADAC (Leicester et al 1995). ACI's Hoop Pine operations were purchased by Hyne and Son in 1996. This report summarises both of these studies and the application of the research results to a commercial timber operation.

Table 2. Summary of visual grading

Visual Grade to AS2858	Grader 1.		Grader 2.		Grader 3.	
	No.	%	No.	%	No.	%
Less than F7	28	9	19	6	29	10
F7	41	14	30	10	36	12
F8 & better	231	77	251	84	235	78

Table 3. Difference between visual graders

Graders	1 and 2		1 and 3		2 and 3	
	No.	%	No.	%	No.	%
Difference by 1 grade	39	13	67	22	57	19
Difference by 2 grades	6	2	15	5	22	7

AS2858 suggests that visual grading in accordance with this standard should be so precise that the maximum variation "between gradings of individual pieces by individual inspectors" should not exceed 5% and not more than 5% of pieces shall fall one stress grade below the designated grade. The origin or documented evidence supporting this requirement is unknown. In this study, three trained and experienced visual graders have independently applied AS2858 to 300 - 190 x 35 ARAKARIA™ and the total difference between the three gradings for individual pieces has been 15%, 27% and 26%. A total of 2%, 5% and 7% of pieces were different by more than one grade. In this case the variation between graders would be unacceptable in accordance with the AS2858 "Variation in assessment" clause. Despite the variation in gradings the resulting structural properties are relatively close. (Refer Table 4.)

Visual grading by its very nature involves the following five steps,

- location of the worst defect.
- identification of the defect.
- measurement of the defect
- comparison of the measurement with a rule
- assigning the piece a grade

All of these activities often need to be performed in just a few seconds and some variation between individual gradings is inevitable. eg. the evaluation of knot area ratios alone, can vary by 10% to 15%. Individual species are also likely to have inherent defects which may cause increased variation in gradings. The sole reason for such a requirement in AS2858 seems to be an acknowledgment that variation can and will occur in visual grading and that this variation between gradings needs to be limited in some way. A 5% limit appears to have been determined arbitrarily. This limit has now been applied by trainers of visual graders as the criteria for assessing grader competency (FAFPESC 1995). While a variation of 5% would seem to be a desirable limit to assist industry in producing a consistently graded structural product, can the AS2858 grading rules be practically applied to this level of precision? The results herein suggest not. Surely this requirement should have been confirmed before inclusion in AS2858!

Making grading rules simpler would seem to be one obvious way of reducing variation between gradings, improving the reliability of visually graded timber and giving increased confidence to visual graders. Alternative and improved means for demonstrating that a particular parcel of visually graded timber is valid could be developed and included in AS2858. eg. establishment of structural properties using AS4063 (Standards Australia 1992), verification of structural properties using ASYYYY(Standards Australia 1996), daily in mill structural testing using an output control system (CEN 1993).

The modulus of rupture and the modulus of elasticity determined for a number of grading options is shown in table 4.

Table 4. Bending Strength and Stiffness Results

Grading Method	No. Sampled	No. Tested	Design MOR (MPA)	Design MOE (MPa)
Red Grade to QTB Appearance Rules	189	70	5.90	10455
F8 to AS2858 Visual Grader 1.	138	31	7.95	10948
Visual Grader 2.	152	42	7.47	10513
Visual Grader 3.	141	35	7.30	10566
AS2858 except knots graded using,				
Edge Width% < 80%	130	29	8.00	11038
Edge Width% < 70%	111	22	7.98	11072
Margin KAR% < 80%	150	39	7.92	11068
Margin KAR% < 70%	135	31	8.24	11024
Red Grade except knots graded using,				
Edge Width% < 100%	172	57	6.26	10669
Margin KAR% < 100%	181	66	5.98	10502
Pith-in pieces only	143	64	5.33	10438

The bending strength required of F8 is 8.6 MPa. Clearly visual grading to AS2858 does not result in a product with this strength. Grading rules which focus on knots near the edge of timber sections appear to be effective at culling out pieces with a low bending strength.

ACI - Hyne Study 1995. A total of 11 small clear specimens were tested in bending. Small clear compression tests were not undertaken as is required by AS 2878 (Standards Australia 1986). Based on the bending test results alone a strength group of SD7 is suggested rather than the current SD5. However, because no compression tests where undertaken a new strength group classification for Araucaria cunninghamii is not justified. Table 5 and 6 summarise the design properties determined for the two sizes tested and for a number of potential grading methods.

Table 5. Design Properties for 140 x 35 Araucaria Cunninghamii.

Grading Method		MOE (GPa)	MOR (MPa)	Tension (MPa)	Compression (MPa)	Shear (MPa)
AS2858	- F11	11.0	7.55	3.99	10.54	1.73
	- F8	11.0	7.23	4.01	9.94	1.72
AS2858 minus HI Rule	- F11	10.9	8.02	3.77	10.99	1.81
AS2858 minus OBS Rule	- F8	11.1	7.55	4.05	-	1.63
Edge & Thru knots only	- < 10%	11.2	8.19	3.95	10.34	2.07
	- < 20%	11.0	7.59	3.76	10.35	1.69
Group knots only	- < 10%	11.3	8.42	3.95	10.78	1.57
	- < 20%	11.3	8.34	3.95	10.84	1.61
MSG Setting	- 7 GPa	11.1	7.55	4.01	-	1.76
	- 9 GPa	12.3	9.19	5.31	11.1	2.18
MSG & Group<20%, Setting	- 7 GPa	11.6	8.32	4.15	10.98	1.72
	- 9 GPa	12.7	10.69	7.70	12.86	2.27

Note: "HI" indicates Heart In and "OBS" indicates Occluded Branch Stubs.

The methods of grading summarised in table 5 and 6 vary in their effectiveness to sort the timber into grades with different mechanical properties. Visual grading in general seems to be relatively ineffective at sorting for MOE but reasonable effective for strength sorting, whereas mechanical stress grading is very effective at sorting for all structural properties. Combined visual and mechanical stress grading is most effective at achieving grades with high strength.

Table 6. Design Properties for 240 x 45 Araucaria Cunninghamii.

Grading Method		MOE (GPa)	MOR (MPa)	Tension (MPa)	Compression (MPa)	Shear (MPa)
AS2858	- F11	11.9	7.29	3.33	10.15	1.63
	- F8	12.8	7.88	4.81	9.20	2.03
AS2858 minus HI Rule	- F11	12.1	8.42	3.96	9.26	2.17
AS2858 minus OBS Rule	- F8	12.3	8.05	3.97	9.64	1.59
Edge & Thru knots only	- < 10%	12.8	8.78	4.89	10.29	1.95
	- < 20%	12.6	8.57	4.42	-	-
Group knots only	- < 10%	12.9	8.49	4.55	9.39	1.92
	- < 20%	12.9	8.74	4.78	10.13	1.94
MSG Setting	- 7 GPa	12.7	7.88	4.94	-	-
	- 10 GPa	14.5	13.21	6.94	13.4	2.27
MSG & Group<20%, Setting	- 7 GPa	13.0	8.70	5.44	10.13	2.47
	- 10 GPa	14.6	13.06	7.22	13.17	3.08

Note: "HI" indicates Heart In and "OBS" indicates Occluded Branch Stubs.

The results given in tables 5 and 6 indicate the following,

- AS2858 is ineffective at sorting timber according to their structural properties.
- Ignoring occluded branch stubs and heart in material had a negligible effect.
- The use of simple knot exclusion rules is an effective means of grading.
- Mechanical stress grading is a useful means of grading this timber.

The above results, together with all of the visual grading options included in the full report (Leicester et al 1995) provide a wealth of information from which a timber producer can develop visual grading rules specific to their needs. For instance should ARAKARIA™ producers wish to develop a customised structural product for a special application then the information from this study could assist in developing appropriate grading rules.

The distance between the tree pith and the centroid of a section was found to have a positive effect on structural properties, in particular bending, tension and compression strength.

APPLICATION OF RESULTS

Hyne Study 1993. Based on commercial considerations regarding grade recovery and the simplicity of potential visual grading rules it was decided to adopt QTB Red Grade rules with the width of knots occurring on edges limited to less than 100% of the piece thickness. A non "F" graded product was developed and marketed as "Hyne Structural 8". The properties of this product were based on the test results with minor structural properties being conservatively estimated from known ratios to bending strength. The recommended properties are shown in Table 7. The properties determined were independently certified, as were the span tables developed for this product.

Table 7. Recommended Structural Properties for "Hyne Structural 8".

Design Property	Bending Strength (MPa)	Modulus of Elasticity (MPa)	Tension Strength (MPa)	Shear Strength (MPa)	Compression Strength (MPa)
Hyne Structural 8	6.26	10670	2.5	0.94	4.7

ACI - Hyne Study 1995. The report from this study (Leicester et al 1995) made no recommendations regarding the application of this information to a commercial grading operation. Hyne and Son obtained the raw test data and reanalysed it before deciding on new visual grading rules for producing an "F7" and "F8" grade of ARAKARIA™. The rules adopted are basically those for Structural Grade No. 4 and 5 of AS2858 except that edge and through knots are limited as follows,

F8	Widths	140 - 170	KAR < 10%
		190	KAR < 15%
		240	KAR < 20%
F7			KAR < 45%

The results of this study may also be used by TRADAC to develop general industry grades for this timber. Draft industry visual grading requirements for F5, F7 and F8 have already been prepared (Hayward 1996) for the consideration of the Standards Australia sub-committee responsible for the review of AS2858.

Hyne and Son will shortly commence the mechanical stress grading of ARAKARIA™ and have used the results of this study to develop settings for the grading of F7 and F8.

CONCLUSIONS

1. Assignment of stress grades to Araucaria cunninghamii using the current AS2858 is inappropriate.

2. Simple visual grading rules based on the exclusion of particular knot types and sizes is an effective way to grade Araucaria cunninghamii.

3. Mechanical stress grading is an effective means of grading this timber.

4. Full size testing together with and an analysis of the influence of various defects provides a multitude of visual grading options.

5. Strength ranking, as described herein, has some potential to reduce the level of testing required to determine structural properties.

6. The 5% variation clause in AS2858 is not practically achievable.

RECOMMENDATIONS

1. The Standards Australia committee responsible for timber grading should,
   i) Respond quickly to evidence of inadequacies in timber grading standards.
   ii) Endorse a suite of unique visual grading rules for Araucaria cunninghamii.
   iii) Provide a means by which company specific grading rules, based on full size testing, can be recognised.
   iv) Develop simpler grading rules.

2. Strength ranking should be further investigated.

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NORMAL SHRINKAGE OF A RECTANGULAR WOOD CROSS-SECTION

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ABSTRACT

A review is given of relationships which determine the shape of dried rectangular wood cross-sections. A numerical example is then described in which the relationships are used to determine the dried shape and where the shrinkage strains are determined from measurements of the dried board section.

Symbols

e shrinkage strain parameter; final length/initial length

α angle made by side of board to radial direction after shrinkage

β angle made by side of board to radial direction before shrinkage

γ shear strain angle; equation (6)

ε shrinkage strain; change in length/original length, $\varepsilon = 1\text{-}e$

Subscripts

1,2 distinguish adjacent sides of board cross-section

r radial

t tangential

θ angular

p relating to perpendicular distance between opposite sides

INTRODUCTION

Some analysis has been published recently which I believe simplifies and makes more complete, calculations relating to the normal shrinkage of a rectangular wood cross-section (Hunter, 1995). The purpose of the present work is to present some of the

Large values of shrinkage percentages have been taken so that the Figures are easier to read.

By (1) then e_θ is 0.8. Let the angles β_1 and β_2 be 60° and 30°. From (5) then

$$\alpha_1 = 54.18°$$

$$\alpha_2 = 24.79°$$

Hence from (6)

$$\gamma = 11.03°$$

From (7*) and (8*) we calculate

$$e_{p1} = 0.7022$$

$$e_{p2} = 0.6290$$

Since the angles and the spacing of the sides are then known, the dried shape is thus specified.

Consider now the reverse procedure where we wish to estimate shrinkage strains from measurements on the dried board section. It is assumed that the board was rectangular in the green state. Taking a corner of the dried board cross-section where the interior angle is less than 90° (normally there will be two such corners), γ is 90° minus the interior angle. The α_1 and α_2 which must add to the interior angle, divide the interior angle at the radial line through the corresponding corner. Referring to Fig.2 we may measure the perpendicular strains e_{p1} and e_{p2} as say 0.70 and 0.63 respectively. For γ, α_1 and α_2 we may find respectively 11°, 54.2° and 24.8°. From (2) we estimate β_1 as 60°. From (4) then we find $e_\theta = 0.8$ (which corresponds to an angular shrinkage of 20%). For e_r we must use (9*) or (10*) and we find $e_r = 0.75$ (radial shrinkage 25%). From (1) then $e_t = 0.6$ (tangential shrinkage 40%).

The effect of inaccuracy of measurement

If the α_1 and α_2 are measured to the nearest degree, that is 54° and 25°, equations (6) and (4) give $e_\theta = 0.801$. With measured e_{p1} and e_{p2} values of 0.70 and 0.63, the e_r values calculated from (9*) and (10*) are 0.7500 and 0.7478. If γ is measured as 12° instead of 11° the value calculated for e_θ from (4) with β equal to 60° or 30° is 0.784 compared with 0.8.

For an actual dried timber cross-section, the angles α_1 and α_2 could be measured for each corner and the results averaged.

DISCUSSION

When working from the measurements of the dried cross-section to the calculation of the shrinkage strains, we have used equations which are as insensitive to the measurements as possible. For example, since γ is usually small, cos γ is relatively insensitive to its measurement (Rêfer to (9*) and (10*)). Also we have worked in terms of the perpendicular strains between opposite sides which are much more reliably measured than the lengths of the sides. The work of Booker *et al* (1992) solves this problem by evaluating the basic equations numerically. Here, the equations are solved analytically and computations then become trivial.

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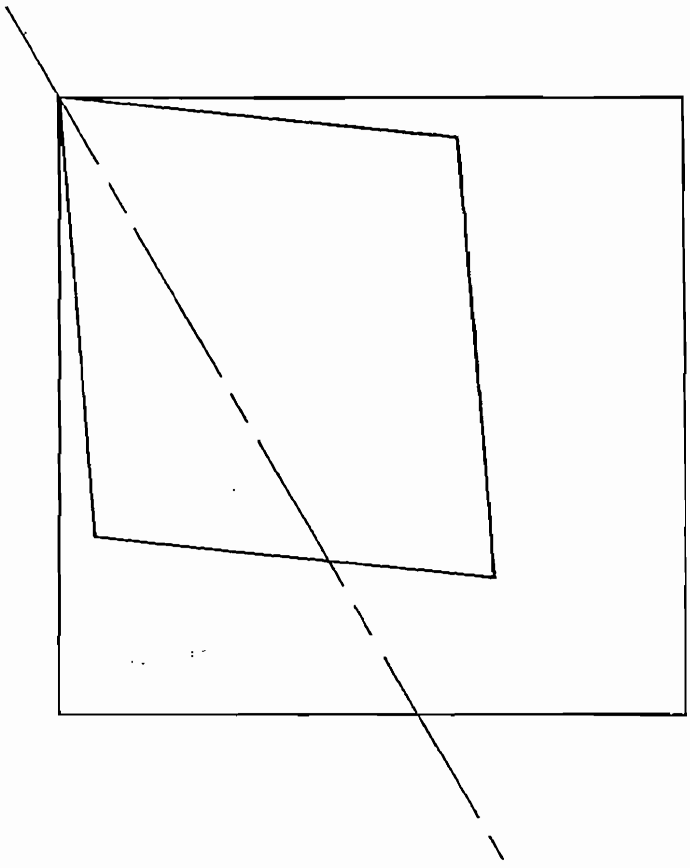

Fig.1. Shrinkage of a small board cross-section which was square in the green condition. The discontinuous line represents the radial direction.

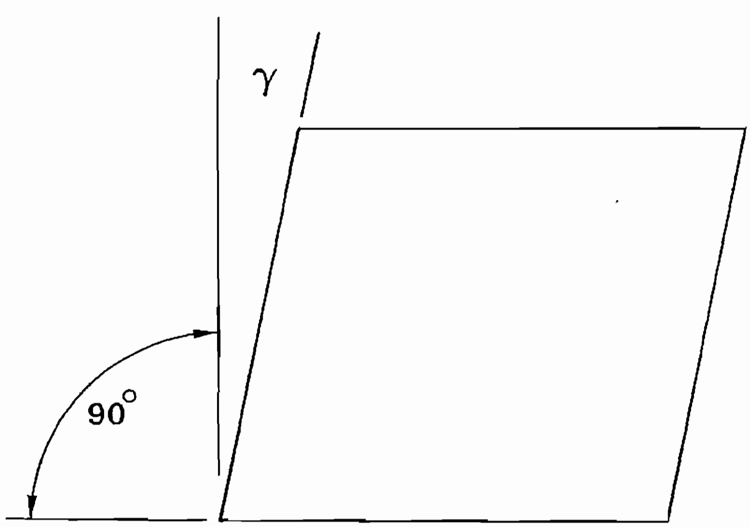

Fig.2. The dried cross-section showing the definition of the shear strain angle, γ.

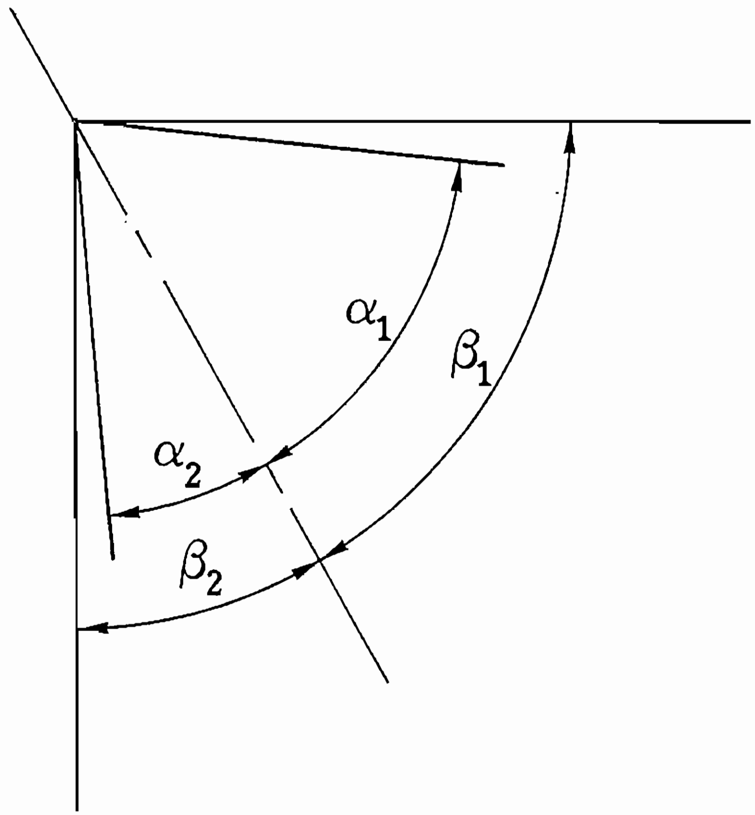

Fig.3. Distortion of a board corner initially at right angles which is specified by equations (5).

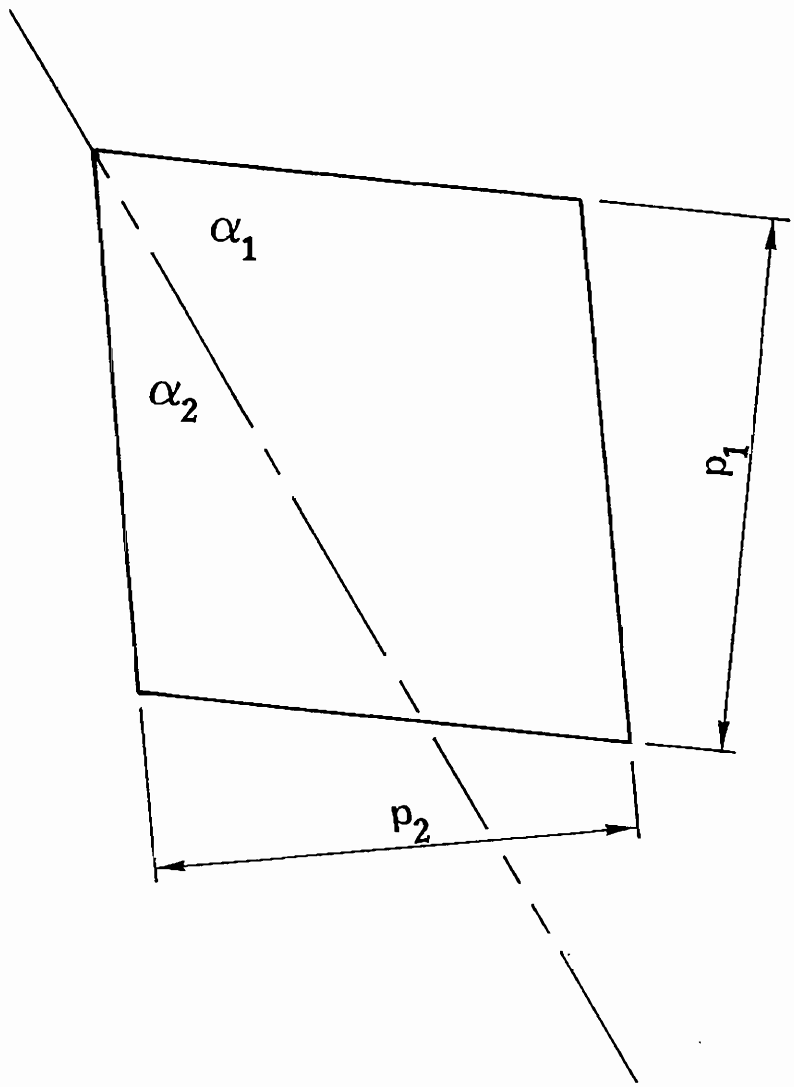

Fig.4. Showing the perpendicular distances between opposite sides and the associated α values.

GOLDFIELDS TIMBER RESEARCH PROJECT

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Western Australia.

BACKGROUND

There are approximately three million hectares of woodland around Kalgoorlie in the Eastern Goldfields Region of Western Australia which have regenerated following harvesting for fuelwood and mining timber since the gold discoveries of the 1890s. A large number of species, predominantly *Eucalyptus*, have considerable economic potential because of the grain, figure and colour of their wood, although their high wood density makes sawmilling, drying and processing difficult.

Potential uses include musical instruments, turnery, furniture and flooring. Professor Felix Skowronek of the University of Washington has carried out assessments of the potential for these species for musical instrument use, particularly as flute heads. The Goldfields Specialty Timber Industry Group (GSTIG) was set up by Goldfields residents whose main interest was in the use of craftwood for turnery, although there were two commercial interests involved. A successful timber seminar in June 1992 showed considerable interest from the local community.

There were few data on the wood properties of most of the Goldfields timber species, and little work had been done on sawmilling, drying and processing. A local company, Timbers of the Goldfields (now Desert Timbers), had experimented with improved sawing methods, and then installed a CALM Solar-assisted Timber Drying Kiln for commercial drying. There was an obvious need for research and development.

PROJECT

In 1994 the GSTIG, in association with Kalgoorlie College and CALM, successfully applied for a Regional Initiatives Fund Grant from the Department of Commerce and Trade to carry out an extensive research and development project of Goldfields timbers, including assessment of wood properties, logging, sawmilling, drying, processing, and manufacturing. This grant was supplemented by funding from the Goldfields Esperance Development Corporation and from CALM.

Responsibilities for the various stages of the Project were organised as follows:

- Logging (Timbers of the Goldfields with assistance from CALM)
- Sawmilling (Timbers of the Goldfields with 'in-kind' assistance from GSTIG members)
- Drying (Timbers of the Goldfields with assistance from CALM)
- Wood properties assessment (Kalgoorlie College, using a part-time Research Technician trained by CALM)
- Processing and demonstration (GSTIG, Timbers of the Goldfields, CALM).

A part-time Technical Officer based in Kalgoorlie was subsequently appointed to handle the CALM input into the Project.

The Project has concentrated on the six species considered to have most economic potential (i.e. redwood (*E. transcontinentalis*), Goldfields blackbutt (*E. lesoeufii*), gimlet (*E. salubris*), salmon gum (*E. salmonophloia*), black morrel (*E. melanoxylon*), and red morrel (*E. longicornis*).

A Steering Committee meets quarterly to control the Project, with the following membership: GSTIG (Chair), GEDC, Timbers of the Goldfields, Kalgoorlie College, and CALM.

DATA COLLECTION

A series of standard forms and spreadsheets was developed to cover all aspects of the research program.

Logging Research

The logging information recorded is as follows:

- species
- form and taper
- location by GPS
- soil and landform details
- tree-boring results (e.g. drilling to assess decay).

These data can be coordinated with the extensive Inventory Program currently being carried out by CALM.

Regional office staff at CALM have some logistics problems in carrying out harvesting operations when large logs are involved, and on occasions interaction with Timbers of the Goldfields is required because the company has specialised logging equipment.

Sawing Research

Data recorded are as follows:

- log dimensions
- log faults
- board dimensions
- green sawn recovery (based on log volume).

Timbers of the Goldfields carried out considerable R & D on sawmilling, including the systematic modification of saw gullets and use of stellite-tipped teeth to handle these very high density species. Consequently, the company is well placed to carry out milling research.

not prepared to pay a premium above jarrah prices. This situation will change with unique applications becoming available from time to time, for example the extensive use of Australian specialty timbers in Parliament House in Canberra.

CALM will continue to promote the use of Western Australian specialty timbers, and as part of the promotion will be preparing hand samples of Goldfields timbers as well as the more common timber species.

FURTHER DEVELOPMENT OF COMPUTER PROGRAM "WOODRY" FOR THE SIMULATION OF HIGH-TEMPERATURE PINE DRYING

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ABSTRACT

This paper describes the development and application of a graphical software package for the simulation of high-temperature, radiata pine drying based on a one-dimensional finite difference method. Using the latest formulations for capillary flow, vapour diffusion and stress analysis, various wood state variables are plotted as functions of distance and time. Some comparisons with the results of experiments are also presented.

INTRODUCTION

Research at the CSIRO Division of Forestry and Forest Products in Clayton, Victoria, Australia has produced two physically-based, simplified mathematical models of the one-dimensional convective high-temperature drying process for *Pinus radiata* (Sutherland, Turner and Northway, 1992, 1994; Sutherland, 1993). These models were converted into two versions of a digital computer program named WOODRY. One of these (Version SM1) was assessed by Kamke and Vanek (1994) in their comparison of wood drying models. The heat and mass transfer model was also combined with a stress development model by Viljoen, Sutherland and Hunter (1994) for the purpose of drying kiln control.

Recent work by Slade, Hunter and Sutherland (1996) has combined the two simplified models into one incorporating the best features of each, and made use of the latest formulations for vapour diffusion, liquid capillary flow and stress analysis derived by Hunter (1993, 1995). A graphical software package for the one-dimensional drying of radiata pine (both low and high temperatures) has been completed for constant internal gas pressure, and a version for varying internal gas pressure is now being developed. Output generated includes average moisture content versus time, temperature versus time, and moisture content, stress and strain profiles within the half board.

NOTATION

c_d	Specific heat of dry wood, J kg dry wood^{-1}K^{-1}
c_w	Specific heat of liquid water, J kg water^{-1}K^{-1}
C	Capillarity coefficient, kg water m^{-1} s^{-1} Pa^{-1}
D	Diffusion coefficient, kg water m^{-1} s^{-1} Pa^{-1}
h_s	Latent heat of vaporisation of bound water in wood, J/kg water
K	Thermal conductivity of wood, Wm^{-1} K^{-1}
M	Moisture content of wood, kg water/kg dry wood
M_{fsp}	Moisture content of wood at the fibre saturation point, kg water/kg dry wood
M_{sat}	Saturation moisture content of wood, kg water/kg dry wood
P_c	Capillary pressure, Pa
P_v	Pressure of water vapour, Pa
r	Relative humidity of air, fractional
S	Saturation, fractional
t	Time, s
T	Temperature of wood, °C
x	Distance, m
μ	Absolute viscosity of water, Pa s (μ_o at 0°C)
ρ_w	Basic density of wood, kg dry wood/m³ green wood

THEORY

Mass Transfer

The moisture content change through the wood as a result of free water capillarity and water vapour diffusion is given by:

$$\rho_w \frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(C\frac{\partial P_c}{\partial x}\right) + \frac{\partial}{\partial x}\left(D\frac{\partial P_v}{\partial x}\right) \qquad (1)$$

Hunter (1995) has suggested that the following relationships apply for Southern pine:

$$C = 2.28 \times 10^{-12}\,\mu_o/\mu \qquad (2)$$

and $P_c = -2566.94 - 36510 \exp(-2.03S) + 7362S^{17.66}$ (3)

where $S = (M - M_{fsp})/(M_{sat} - M_{fsp})$

The value of D is given by Hunter (1993) as

$$D = 1.66 \times 10^{-12} + D_f/(1 + 6.59 \times 10^{11}\, D_f\, [(273.15 + T)/313.15]^{2.5} \log_e{}^2 r) \quad (4)$$

where for Scots pine D_f can be taken as 6.45×10^{-11}.

Heat Transfer

The temperature change through the wood as a result of evaporation and conduction is given by:

$$\rho_w (c_d + c_w M) \frac{\partial T}{\partial t} = h_s \frac{\partial}{\partial x}\left(D \frac{\partial P_v}{\partial x}\right) + \frac{\partial}{\partial x}\left(K \frac{\partial T}{\partial x}\right) \quad (5)$$

The heat and mass transfer coefficients required for the boundary conditions at the wood surface are taken from Pang (1996).

RESULTS AND DISCUSSION

Sutherland, Turner and Northway (1992) compared predictions of two simplified drying models with four experimental drying runs by Northway (1989) covering air temperatures from 90 to 150°C and air velocities from 3 to 8 m/s. It was found that although wood temperatures and average moisture contents were predicted reasonably well, moisture profiles were not. Recent changes to the model have improved this situation markedly.

In Table 1, actual and predicted average and centre wood moisture contents at the end of drying are compared for the four runs; it can be seen that predictions are within 1% for average m.c. and 2% for centre m.c.

TABLE 1

Comparison of actual and predicted average and centre wood moisture contents at the end of the drying period (from Slade, Hunter and Sutherland, 1996)

Run	Time (h)	Average m.c. (%)		Centre m.c. (%)	
		Actual	Predicted	Actual	Predicted
1	92	8.6	8.2	10.0	10.0
2	18	16.0	16.0	21.9	24.3
3	12	13.0	12.8	21.8	22.0
4	6	20.0	19.3	27.1	25.9

Figure 1 shows predicted m.c. profiles for Run 2 where it can be seen that the actual profile at the end of drying (18 h) compares very well with the predicted one. The effects of capillary flow and vapour diffusion above and below fibre saturation point (FSP) respectively can be clearly seen (at inflection points on the curves), and the experimental plateau at a value of 22% m.c. corresponds to the FSP for a temperature of 100°C. Profiles of temperature, stress and strain for Run 3 (extended to 24 h) are shown in Figures 2, 3 and 4 respectively. The phenomenon of stress reversal is clearly seen in Figure 3.

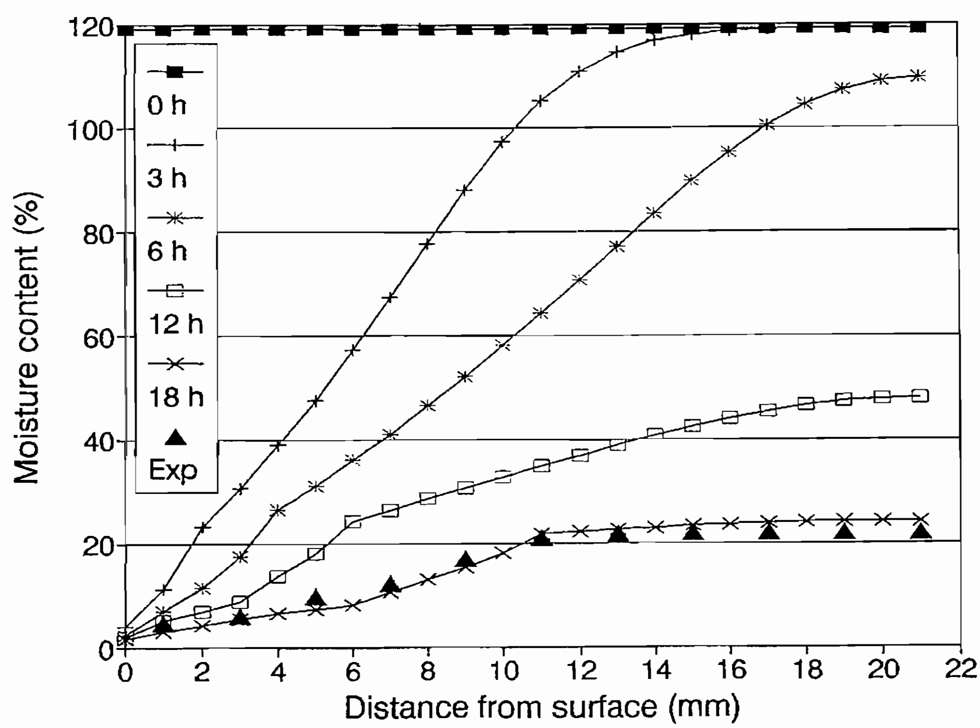

Fig. 1. Predicted wood moisture content profiles in the half board for Run 2 with experimental values at the end of drying (18 h) also shown (from Slade, Hunter and Sutherland, 1996).

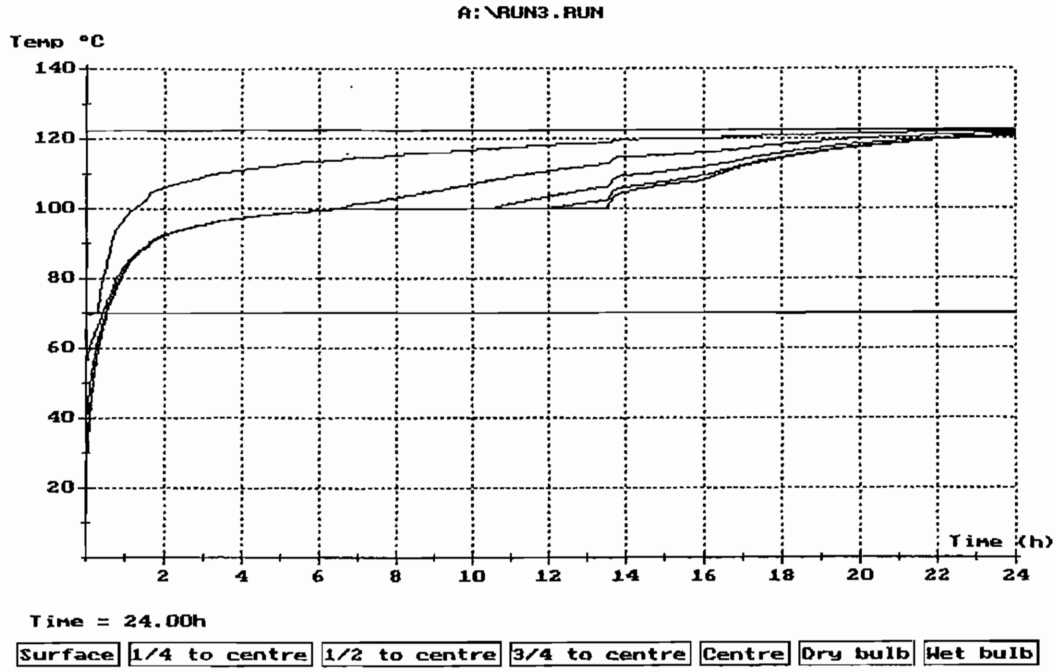

Fig. 2. Predicted wood temperature profiles for Run 3. The dry and wet-bulb temperatures are 122 and 70°C respectively. The surface and centre values are the highest and lowest respectively.

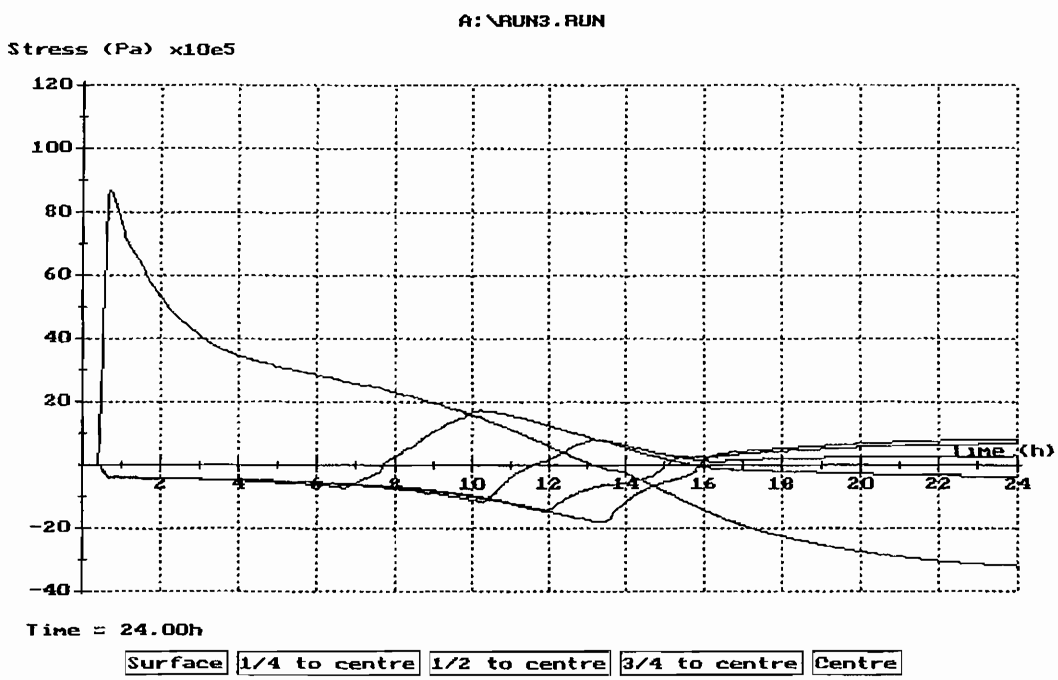

Fig. 3. Predicted stress profiles for Run 3 (from Slade, Hunter and Sutherland, 1996). The surface value is the highest. The centre value is the lowest up to approximately 14h.

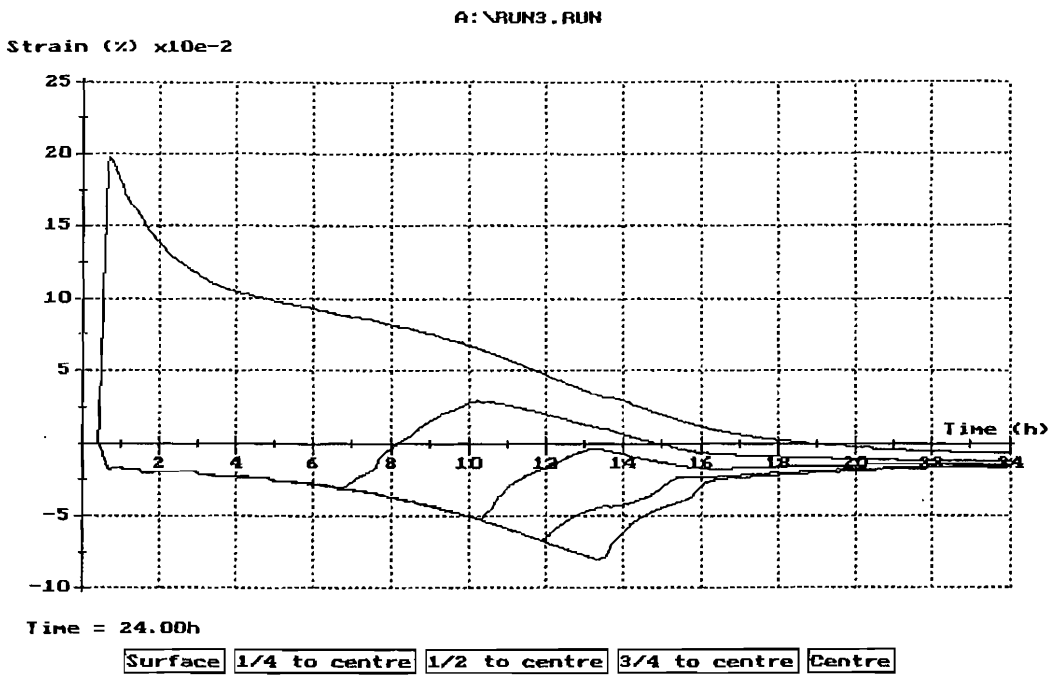

Fig. 4. Predicted strain profiles for Run 3 (from Slade, Hunter and Sutherland, 1996). The surface and centre values are the highest and lowest respectively.

It is shown in Table 2 that whereas maximum surface stress and strain increase by 25-30% for an increase in air temperature at the same velocity (from Run 1 to Run 2 and from Run 3 to Run 4), the increase is 74-82% for a change in air velocity from 3 to 8 m/s at approximately the same temperature (from Run 2 to Run 3). For comparison, the critical value of instantaneous strain at the surface to produce checking of eucalypts suggested by Oliver (1991) is 2%.

TABLE 2

Predictions of surface stress and strain for different drying air conditions (from Slade, Hunter and Sutherland, 1996)

Run	Dry-bulb temp. (°C)	Wet-bulb temp. (°C)	Air velocity (m/s)	Max. surface stress (MPa)	Max. surface strain (%)
1	90	70	3	4.0	0.085
2	125	70	3	5.0	0.11
3	122	70	8	8.7	0.20
4	152	67	8	11.0	0.26

CONCLUSIONS

A simplified one-dimensional model of the pine drying process, based on the laws of physics and employing an explicit finite-difference method of solution, has led to a user-friendly graphical software package, which can yield ready comparisons of different kiln drying schedules in terms of drying performance and timber quality.

Predictions using the computer program have been shown to satisfactorily match observed wood moisture contents, temperatures and drying times for practical purposes. Program WOODRY should be useful for the researcher, engineer and drying kiln operator alike.

ACKNOWLEDGEMENTS

The financial support of CSR Timber Products and Windsor Kilns for this work is gratefully acknowledged. Vacation student, Teo Groza, is thanked for his assistance with the graphical software package.

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Oliver, A.R. (1991). A model of the behaviour of wood as it dries. University of Tasmania, Research Report CM91-1.

Pang, S. (1996). External heat and mass transfer coefficients for kiln drying of timber. Drying Technology, Vol. 14, No. 3-4, pp. 859-871.

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Sutherland, J.W., Turner, I.W. and Northway, R.L. (1992). A theoretical and experimental investigation of the convective drying of Australian *Pinus radiata* timber. Proc. 3rd IUFRO Int. Wood Drying Conf. (M. Vanek. ed.), Vienna, Austria, August, 1992, pp. 145-155.

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Viljoen, J.P.S., Sutherland, J.W. and Hunter, A.J. (1994). Supervisory control of kiln drying using an on-line model of combined moisture movement and stress development. Proc. 4th IUFRO Int. Wood Drying Conf. (A.N. Haslett and F. Laytner, compilers), Rotorua, New Zealand, August, 1994, pp. 321-328.

TIME DEPENDENT MOISTURE DIFFUSION MODELS FOR TIMBER

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SUMMARY

Mathematical predictions of mechano-sorptive deformation of timber depend upon an accurate estimation of the moisture distribution. In this paper, one dimensional and two dimensional time dependent moisture diffusion models are presented which are ultimately intended for use in a more comprehensive model for evaluating mechano-sorptive creep, especially the creep of glulam. The moisture models have been converted to computer codes to produce numerical results given herein which are then compared with the results of other researchers in the field.

1 INTRODUCTION

The writers' primary aim is to study mechano-sorptive behaviour of glulam in particular. A fundamental rperequisite is a mathematical model for determining the moisture distribution within the glulam. The assumptions made in developing these models are as follows.

I. Any change in the service environment (expressed as a moisture content of the surface wood) can be expressed in terms of a Fourier sine series; data is available from Cole.[1]

II. The face bond lines act as moisture barriers. Thus moisture diffusion is one dimensional in the inner and two dimensional in the two outer-most laminations.

It has been accepted for some time that the moisture distribution in a piece of wood can be described by Fick's Law, eqn 1. The use of Fick's Law has the obvious advantage that it is mathematically analogous to the heat diffusion equation which has been investigated extensively by mathematicians. These solutions have been documented extensively by Carslaw and Jaeger[2] and Obert[3]. Heat diffusion solutions are available of both analytical and numerical type. The most convenient are closed form solutions, preferably ones not involving slowly converging series summations.

$$D_x \frac{\partial^2 m}{\partial x^2} + D_y \frac{\partial^2 m}{\partial y^2} = \frac{\partial m}{\partial t} \qquad 1$$

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[1] Cole, ID, **Estimation of the EMC within a timber stud in a Melbourne wall cavity, CSIRO Internal Report**, April 1993.

[2] Carslaw, HS, Jaeger, JC,[1986] **Conduction of Heat in Solids**, Clarendon Press, Oxford.

[3] Obert, EF, [1968] **Boundary value problems of heat conduction**, International text Book Company, pp 43-79.

where, m = moisture content %, x, y = coordinate axes, t = time, D_x, D_y = moisture diffusion coefficients.

Leicester and Lu[4,5,6] have presented analytical solutions of Fick's Law for one and two dimensional moisture diffusion. In this paper, alternative one dimensional analytical solutions are presented and compared with these. Two solutions are also discussed.

2 ONE DIMENSIONAL SOLUTIONS

Fig 1 represents section of a glued laminated timber member. If the glue lines are regarded as impermeable then, except for the outer-most laminations, the moisture flow is one-dimensional.

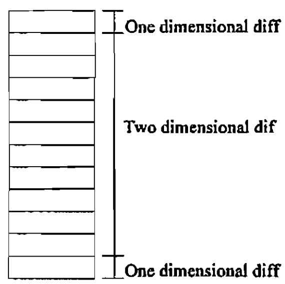

Fig 1 Glulam member with impermeable face bond lines.

2.2 Slab Bounded by Two Parallel Planes: Cyclic change in surface moisture - analytical solution after Carslaw and Jaeger

The case of cyclic moisture variation $m = m_0 + m_a \sin(\omega t + \varepsilon)$ at the surface of a one dimensional "slab", after adjustment for notation, is given by Carslaw and Jaeger[7] as

$$m = A \sin(\omega t + \phi + \varepsilon) \qquad 2$$

where

$$A = m_a \left| \frac{\cosh[kx(1+i)]}{\cosh[kL(1+i)]} \right| = \left\{ \frac{\cosh(2kx) + \cos(2kx)}{\cosh(2kL) + \cos(2kL)} \right\}^{0.5},$$

$$\phi = \arg\left\{ \frac{\cosh[kx(1+i)]}{\cosh[kL(1+i)]} \right\} = \arg\left\{ \frac{\cosh(kx)\cos(kx) + i\sinh(kx)\sin(kx)}{\cosh(kL)\cos(kL) + i\sinh(kL)\sin(kL)} \right\}$$

[4] Leicester, RH, Lu, JP,[1992] **Effects of shape and size on the mechano-sorptive deformations of beams** ProcIUFRO S.502, Timber Engineering meeting, Bordeaux, France, 17-21 August.

[5] Leicester, RH, Lu, JP,[1994] **Studies of mechano-sorptive effects, Part 1: Mechano-sorptive effects on strength and stiffness.**

[6] Leicester, RH, Lu, JP, [1994] **Studies of mechano-sorptive effects, Part 2: Solution of the diffusion equations considering the effects of surface resistance.**

[7] Carslaw, HS, Jaeger, JC,[1986] **Conduction of Heat in Solids**, Clarendon Press, Oxford, pp105-6.

$k = \left(\frac{\omega}{2D_x}\right)^{0.5}$, ω = angular frequency = $2\pi/T$, T = period, ε = phase shift. The term arg is used to indicate the phase or angle of the complex variable and is determined after eliminating i from the denominator. The slab is contained in the region $-L < x < L$. The solution leads to the results shown in Fig 2.

This solution, eqn 3, has transient terms eliminated. These represent the adjustment from, say, a constant to a steady state moisture distribution. The sinusoidal surface moisture change involves a mean value, m_0, and sinusoidal change of amplitude, m_a, and circular frequency, ω.

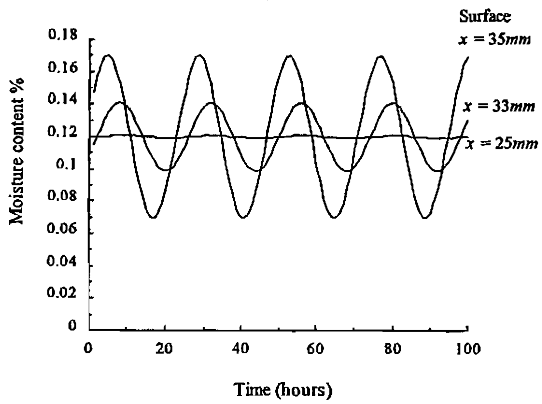

Fig 2 Moisture change in 70*mm* wide "slab". $2L = 70mm$, $D_x = 0.72mm^2/hr$, $\omega = 2\pi/T$, $T = 24hrs$, $\varepsilon = 0$ (no phase shift).

2.2 Slab Bounded by two Parallel Planes: Cyclic change in surface moisture - solution by finite differences

The one dimensional finite difference equation has the following form,

$$m_j^{i+1} = m_j^i + \delta t D_x \left(\frac{m_{j+1}^i - 2m_j^i + m_{j-1}^i}{(\delta x)^2} \right) \qquad 3$$

i indicates the time and j the space step. The results from eqn 3 are given in Fig 3. These results have an almost identical appearance with the results given by eqn 2.

2.3 Solution given by Leicester and Lu for a semi-infinite domain

A semi-infinite domain is the term applied to a region $0 < x < L$, $-\infty < y < \infty$. For this case Leicester and Lu give,

$$m = m_0 + e^{-kx} \sin(\omega t - kx) \qquad 4$$

The results of eqns 2, 3, 4 are shown in Fig 4 for the point $x = 2mm$ from the surface. All results are essentially the same.

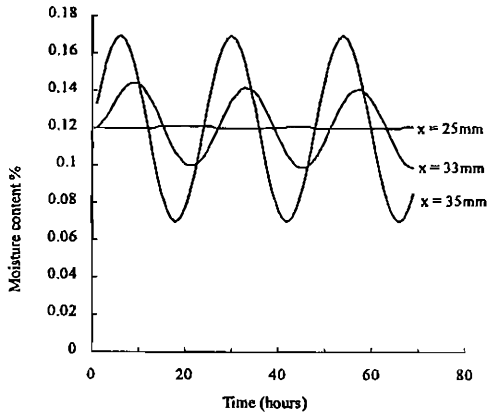

Fig 3 Moisture change in 70*mm* wide "slab". $2L$ = 70*mm*, $D_x = 0.72mm^2/hr$, $\omega = 2\pi/T$, $T = 24hrs$, $\varepsilon = 0$ (no phase shift).

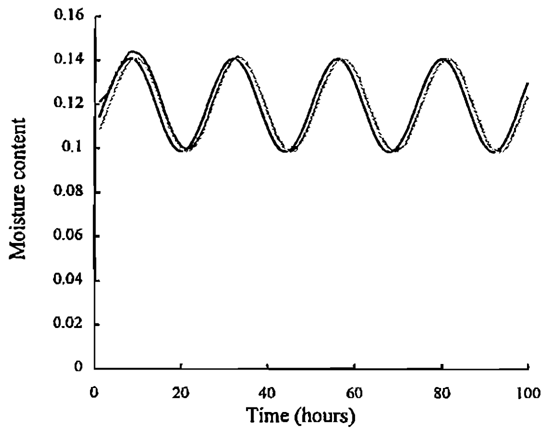

Fig 4 Moisture change in 70*mm* wide "slab". $D_x = 0.72mm^2/hr$, $\omega = 2\pi/T$, $T = 24hrs$ at $x = 2mm$ from the surface.

3 TWO DIMENSIONAL SOLUTIONS

3.1 Solution by Finite Differences

In the two dimensional case, the finite difference expressions are given by,

$$\frac{\partial^2 m}{\partial x^2} = \frac{m^i_{x+1,y} - 2m^i_{x,y} + m^i_{x-1,y}}{(\delta x)^2} \qquad 5(a)$$

$$\frac{\partial^2 m}{\partial y^2} = \frac{m^i_{x,y+1} - 2m^i_{x,y} + m^i_{x,y-1}}{(\delta y)^2} \qquad 5(b)$$

$$\frac{\partial m}{\partial t} = \frac{m^{i+1}_{x,y} - m^i_{x,y}}{\delta t} \qquad 5(c)$$

By choosing equal spatial intervals, the finite difference expression becomes

$$m_{x,y}^{i+1} = m_{x,y}^{i} + \frac{\delta t}{(\delta x)^2}\left\{ \begin{array}{l} D_x\left[m_{x+1}^{i} - 2m_{x,y}^{i} + m_{x-1,y}^{i}\right] \\ +D_y\left[m_{x,y+1}^{i} - 2m_{x,y}^{i} + m_{x,y-1}^{i}\right] \end{array} \right\} \qquad 6$$

which is simple to use because of its explicit form - values at time $t+\delta t$ are determined entirely from spatial derivatives at time *t*.

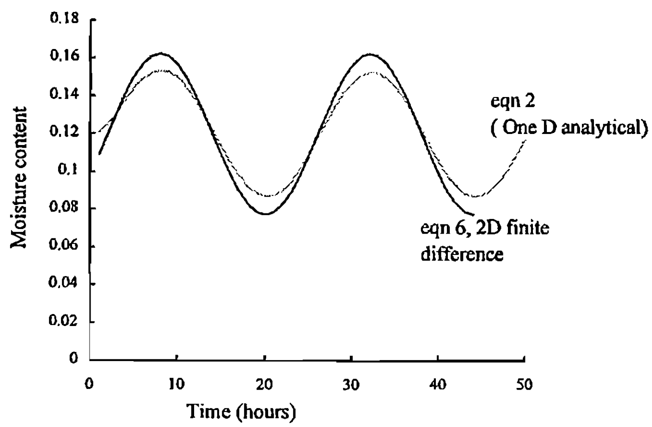

Fig 5 Moisture change in 70*mm* x 35*mm* cross-section. $D_x = D_y = 0.72mm^2/hr$, $\omega = 2\pi/T$, $T = 24hrs$ at $x = 2mm$, in one dimensional model, at $x = 2mm$, $y = 2mm$ in the two dimensional model. Cyclic moisture variation at the surface $m = m_0 + m_A sin(\omega t)$, $m_0 = 0.12$, $m_A = 0.05$.

4 CONCLUSIONS

1. The models of the authors produce results which are substantially in agreement with those of other researchers in the case of one dimensional diffusion.

2. The two dimensional diffusion model produces results in which the moisture variations are greater.

APPENDIX: MECHANO-SORPTIVE BEHAVIOUR OF TIMBER MEMBERS IN BENDING

The total strain is given by

$$\varepsilon = \varepsilon_1 + \varepsilon_2 \qquad A1$$

where ε_1 = elastic strain, ε_2 = mechano-sorptive strain.

The constitutive relationship can only be written in incremental form. Thus the the strain changes must be described incrementally as $d\varepsilon/dm = d\varepsilon_1/dm + d\varepsilon_2/dm$, where m = moisture content.

The writers' work at this stage is not fully developed. The constitutive relationship is restricted to the model illustrated in Fig A1. This differs to the model used by some other researchers in which the spring element is replaced by an elastic-plastic element.

The Fig A1 model has a mathematical relationship of the form. $\frac{d\varepsilon}{dm} = \frac{1}{E}\left(\frac{d\sigma}{dm} - k\sigma\right)$ where k = mechano-sorptive constant = 0 for absorption but is a non-zero constant for desorption that has to be determined experimentally.

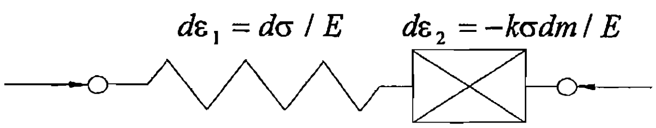

Fig A1: Mechano-sorptive model adopted.

During bending it is assumed that plane sections remain plane and thus a strain increment is given by $\frac{d\varepsilon}{dm} = \frac{d\varepsilon_0}{dm} + y\frac{d\phi}{dm}$ where $d\varepsilon_0$ = strain when y = 0 (section centroid), $d\phi$ = curvature. Increments $d\varepsilon_0$ and $d\phi$ are related to stress, stress increments and moisture increments by

$$d\sigma = Eyd\phi + Ed\varepsilon_0 + k\sigma dm \qquad \text{A2}$$

An increment in axial load and bending moment is given by

$$dP = EAd\varepsilon_0 + k\int_A (\sigma dm) dA \qquad \text{A3(a)}$$

$$dM = EId\phi + k\int_A (\sigma y dm) dA \qquad \text{A3(b)}$$

If the external loads remain constant, then

$$d\varepsilon_0 = -\frac{k}{EA}\int_A (\sigma dm) dA \qquad \text{A4(a)}$$

$$d\phi = -\frac{k}{EI}\int_A (\sigma y dm) dA \qquad \text{A4(b)}$$

For simplicity it is supposed that the moisture diffusion does not vary length-wise. Thus, in the case of uniform bending moment, $dv = \int_0^{L/2} d\phi z dz = d\phi \int_0^{L/2} z dz$ $= d\phi\left(L^2/8\right.$. Hence

$$dv = -\frac{kL^2}{8EI}\int_A (\sigma y dm) dA \qquad \text{A4(c)}$$

Converting eqns A1 and A4(a) and A4(c) to finite difference form leads to

$$\varepsilon_0^{i+1} = \varepsilon_0^i - \frac{k}{EA}\int_A \sigma^i \left(m^{i+1} - m^i\right) dA \qquad \text{A5(a)}$$

$$v^{i+1} = v^i - \frac{kL^2}{8EI}\int_A \sigma^i y\left(m^{i+1} - m^i\right) dA \qquad \text{A5(b)}$$

$$\sigma^{i+1} = \sigma^i + Ey\left(\phi^{i+1} - \phi^i\right) + E\left(\varepsilon_0^{i+1} - \varepsilon_0^i\right) + k\sigma^i\left(m^{i+1} - m^i\right. \qquad \text{A5(c)}$$

Results obtained from eqns A%(a), (b), (c) and the moisture diffusion equation 1 are shown in Fig A1. It differs from some results shown by others for reasons which are not clear. Further investigation is necessary to resolve this matter.

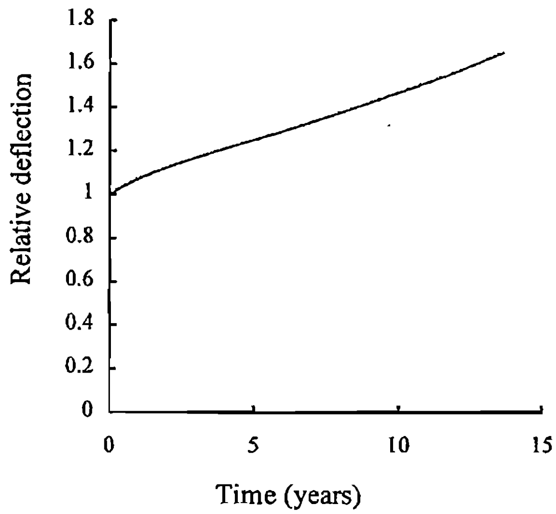

Fig A1 Typical output obtained from mechano-sorptive model. Daily moisture cycles, m_0 = 0.15, m_A = 0.03, D = 420mm, B = 80mm, E = 16000MPa, D_x = D_y = 0.72mm^2/hr, k = 0.2.

Magnetic Resonance Imaging and Spectroscopy of Water During the Drying of Soft Woods

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1. Introduction

The paper presents preliminary results of an NMR investigation of the state and distribution of water in soft woods. This work is part of a large project funded by FWPRDC, Pine Australia, TRADAC, and including participation by QLD DPI Forestry, Univ. of QLD, QLD Univ. Technol., Univ. Melbourne, CSIRO Wood Science and Technology, and CSR. Broadly stated the aims of the project are to determine the properties responsible for distortion in soft wood during and after drying. The methodology adopted includes studies of the distribution and state of water by NMR imaging and spectroscopy, modelling of transport processes, and studies of the changes in microstructure during the drying process using XRD, neutron scattering, ESEM, SEM, scanning confocal microscopy, etc.. The following paper presents preliminary DMA and TGA results. Microscopy results will be presented during the poster sessions

^{1}H NMR Spectroscopy

^{1}H NMR spectroscopy is a convenient method for determining the number and type of proton nuclei, i.e. hydrogen atoms, in a material. In heterogeneous solids the NMR line width arises from dipole-dipole couplings between near-neighbour protons. The strength of this interaction is diminished markedly by molecular reorientation processes, and hence the NMR line shape provides information on the motion of the water molecules in wood. In practice the NMR signal we observe contains a broad underlying signal due to rigid materials, and a superimposed narrow line due to the water, either "bound" or "free". There is no clear distinction between "bound" and "free" water.

NMR Relaxation Times

NMR spectroscopy is a time domain experiment, i.e we collect the NMR signal over a period of time of several microseconds up to many milliseconds. This implies that NMR can be used to measure molecular motion, and other processes which occur over this time scale. In the NMR experiment, we establish an equilibrium set of energy levels in our protons, and perturb this equilibrium with a short pulse of radio frequency energy. The NMR signal is observed as a return to equilibrium. The rate of return to equilibrium is described by a set of time constants called relaxation times.

Three relaxation times are of importance in ^1H NMR spectroscopy. Firstly the rate of exchange of energy in the transverse plane is described by the time constant $\mathbf{T_2}$. Loss of energy to the surrounding material, in the form of lattice vibrations and thermal energy occurs with a time constant $\mathbf{T_1}$. Finally in a spin-locking experiment the rate of relaxation is described by the spin-lattice relaxation time in the rotating frame, or $\mathbf{T_{1\rho}}$. The last two parameters are sensitive to molecular exchange processes, while T_2 relaxation time provides a rapid measure of the number of different protons in the material.

NMR Imaging

NMR Imaging (MRI) exploits the fact that the NMR frequency is directly proportional to the magnetic field experienced by the proton nuclei. In NMR spectroscopy a constant field is applied to the sample and therefore all the signals appear at the same or similar frequency. If however, a strong linear gradient of magnetic field is applied across the sample, the NMR frequency will depend on the position of the nuclei along the line of that gradient. The NMR signal is said to be "spatially-encoded". The NMR spectrum then is a representation of the concentration of ^1H nuclei along that gradient. For example a "slice" through a spherical sample will produce a hemi-sphere on the frequency axis of the NMR spectrum. If the sample principles are applied in all three dimensions a 3-dimensional image can be reconstructed, where the frequency describes the position, and the intensity describes the number of spins at that particular position. The NMR Imaging experiment can be combined with any of the relaxation time experiments, to provide 3D maps of the various types of water in wood samples.

2. Experimental Part

The samples used were a fresh sample of green *Pinus caribaea* morelet var. hondurensis barett & golfari (WW-A), a sample retained at 4 °C for one month (WW-B), and a sample of kiln-dried wood kept at ambient conditions for one month (DW).

^1H NMR spectra were recorded on a Bruker MSL 300 spectrometer operating at 300.13 MHz, and using a home-built ^1H NMR probe. The $\pi/2$ pulse time was 3.5 µs. Spectra were recorded with a sweep width of 2.5 MHz. The inversion recovery method was used to measure T_1, with typically 64 spectra recorded per T_1 measurement. The relaxation time $T_{1\rho}$ was measured using a spin locking field of 71 kHz, and duration up to 30 ms. Relaxation times were determined from the data using a NLLS fitting algorithm.

NMR Images were obtained using an AMX 400 spectrometer operating at 400.13 MHz. The spin-echo 3D sequence was used to obtained all images which were either of size 256x256x256 or 256x256x8. The resolution in-plane was 40 µm, and slice thickness either 120 µm or 4 mm. Echo times were varied from 5 - 15 ms.

3. Results and Discussion

^1H NMR Spectroscopy

^{1}H NMR spectra for the samples of kiln-dried (DW) and 4 °C equilibrated wood (WW-B) are shown in Figure 1 and 2, respectively. The spectra demonstrate changes in the water content and state of the bound water. The spectrum of "dry" wood consists of a broad background signal due to rigid parts of the samples, i.e. cellulose, hemicellulose and lignin, and a superimposed narrow signal due to water. The linewidth of the peak due to water is substantially larger than the peak due to water in the green sample, indicating that the water in the "dry" timber is more strongly bound than in the green sample. In addition it is clear that the concentration of the water is very much greater in the green sample, being 56% of the NMR signal compared with 21.5% in the dry sample.

Figure 1 ^{1}H NMR spectrum of dry wood (DW) and integral.

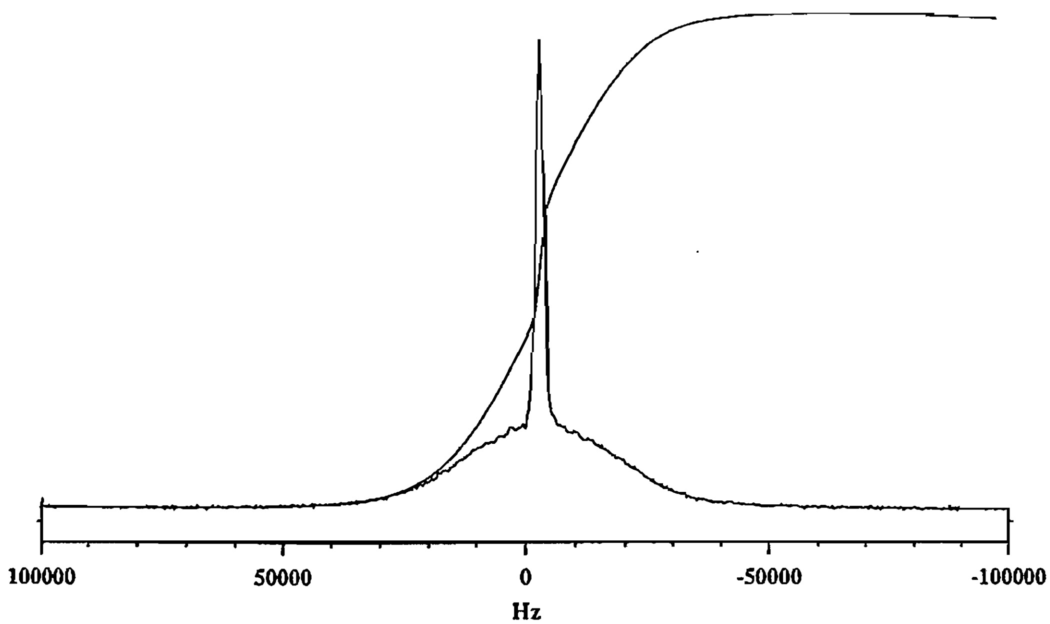
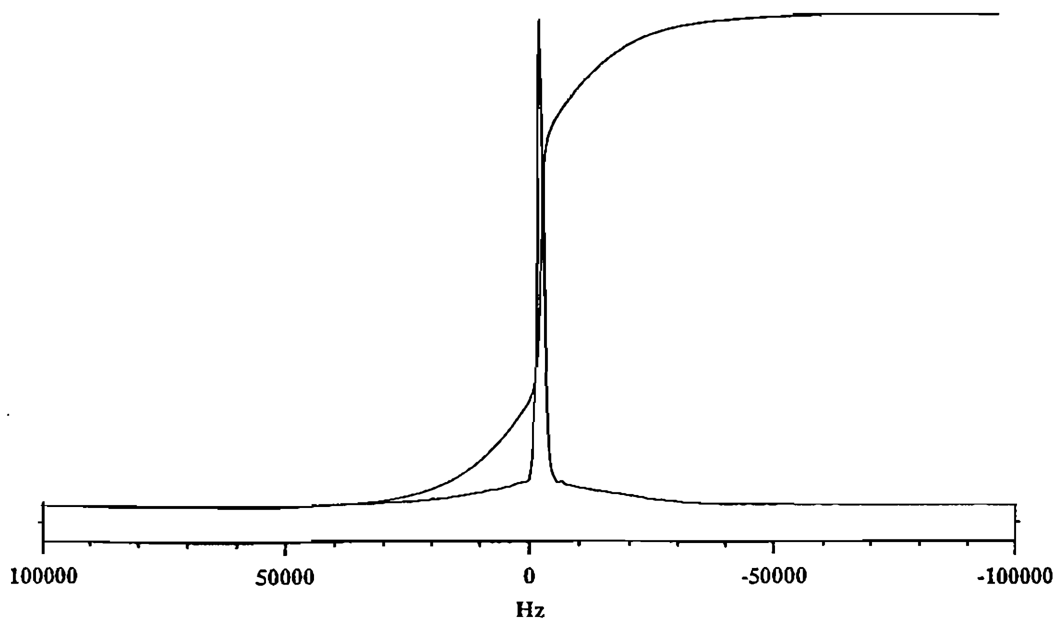


Figure 2 ^{1}H NMR spectrum of wet wood (WW-A) and integral.



As mentioned above, previous workers have attempted to resolve two components in the NMR spectra due to different states of water. These have been assigned in the literature to water "strongly bound" to the polymer chains, and "mobile" water respectively. We have no evidence to support these previous assignments. It is highly likely that the bound water will be in exchange with water molecules removed from the surface of the polymer chains. The rate of exchange will of course be dependent on a number of factors, but will normally be sufficient to produce a composite line shape for both mobile and bound water, with a linewidth intermediate between the two extremes. The NMR line shape therefore reflects the average state of water. Furthermore, our experiments have tended to show that there exists a continuum of states of water from strongly bound to "free" water.

Recent results of T_2 measurements after a range of different thermal treatments will also be discussed.

NMR Relaxation Times

NMR relaxation times for the three samples studied are shown in Table 3.1.

Table 1 T_1 and $T_{1\rho}$ values of green timber WW-A and kiln-dried timber DW.

Sample	Signal	T_1 (ms)	$T_{1\rho}$ (ms)
Green Sample (WW-A)	Narrow Peak	8.5 (8%) 131.8 (92%)	1.8 (50%) 10.9 (50%)
	Broad peak	112.1	8.0
Dry Wood Sample (DW)	Narrow Peak	27.7 (9%) 290.7 (91%)	0.6 (18%) 2.1 (82%)
	Broad Peak	270.5	5.8

It is best to deal with the information in this Table in point form. Concentrate initially on the column second from the right, i.e. the T_1 results for green and dry wood.

1) For both green and dry wood a single T_1 is seen for the broad peak (rigid part), while two T_1s are resolved for the water. This does not indicate two types of water - see below.

2) The second T_1 for the narrow peak is very similar to that for the broad peak. This indicates that exchange between free and surface water is occurring rapidly on this time scale (100-200 ms), and that we see an averaging of amplitudes and time constants for water.

3) On drying, the T_1 for the broad signal increases. This indicates a slowing of molecular motions, probably due to anti-plasticisation by loss of intra-cellular water. Similarly the T_1 for the narrow peak increases, probably due to changes in viscosity.

4) As alluded to above one would normally expect the T_1 for the mobile water to

be much longer than the 10 ms observed. This must reflect the higher viscosity of this water compared to pure water, or alternatively may be due to the presence of dissolved paramagnetic ions.

The right hand column of Table 1 shows the results of the $T_{1\rho}$ experiment. The conclusions deduced from this data are:

5) The longer $T_{1\rho}$ for the narrow peak is close to that for the broad peak, again indicating that the water molecules are in rapid exchange over this time scale (10 ms).

6) For green wood a higher proportion of the fast $T_{1\rho}$ is seen compared to the relative proportions seen in the T_1 experiment, since during $T_{1\rho}$ relaxation the water molecules diffuse during 1-10 ms, compared to 100-200 ms during the T_1 experiment. Therefore, averaging of the signals is less complete.

7) On drying, the proportion of the short $T_{1\rho}$ decreases, and this reflects the decrease in a thickness of the water layer on drying.

8) The decrease in $T_{1\rho}$ of the broad peak on drying also indicates a slowing of molecular motions due to loss of water.

Magnetic Resonance Imaging

Figures 3-5 show MRI images of the water distribution in three samples of wood. The samples are a green timber (WW-A) (Fig 3), a sample of green wood stored 4 °C for one month (WW-B) (Fig. 4), and a sample which has been kiln-dried at 160 °C (DW) (Fig 3.9). The samples were small blocks of dimension 8mmx8mmx20mm. The images are shown as stack plots of slices through the width of the block. The vertical axis shows intensity of the NMR signal i.e. water concentration, while the horizontal plane shows position through the slice of the block.

Several points are immediately apparent. Firstly, the water in green timber (WW-A) is confined to the early wood, and appears to be evenly distributed across the bands of early wood. The concentration of water in the late wood is low (see Fig. 3). For the sample equilibrated at 4 °C (WW-B), the overall concentration of water in the bands of early wood has decreased, and some structure is now visible. There appears to be a proportion of tracheids which have retained an appreciable concentration of water. The nature of the water in this image is discussed below.

The water in the kiln-dried wood (DW, Figure 5) seems again to be of two types. Firstly there persists a significant concentration of water trapped in tracheids. The background concentration of water is now constant across both the early and late woods. It appears that drying has lead to an increase in the concentration of water in the late wood tracheids.

The latest results, including T_2-weighted images will be presented at this meeting. This last experiment allows us to distinguish between tracheid and cell-wall water.

Dynamic Mechanical and Thermal Gravimetric Analysis of the Drying of Soft Woods

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1. Introduction

Dynamic Mechanic Analysis (DMA) is a technique which measures the response of a material to deformation, at a constant or variable frequency, over a range of temperatures. The sample in our experiment is a small block of approximate dimension 20mmx10mmx2mm, although DMA can be used in a large number of different geometries.

Many materials display viscoelastic properties, i.e. the response to an applied force is the combination of an elastic response, where stress is proportional to strain, and a viscous response, where stress is proportional to strain rate. The respective properties are measured by applying to the sample an oscillating stress field. The stress is measured as force per unit area, and the strain as change in length of the sample divided by the original length. Figure 1 shows the response of a viscoelastic material to an applied oscillating stress. In such a material the strain, or response of the material, lags somewhat behind the applied strain, by an angle δ, which is a measure of the ability of the material to absorb energy at this frequency. The stress and strain cycles shown in Figure 1 are given by the expressions:

$$\delta = \delta_o \sin(\omega t+\delta) \qquad \varepsilon = \varepsilon_o \sin(\omega t)$$

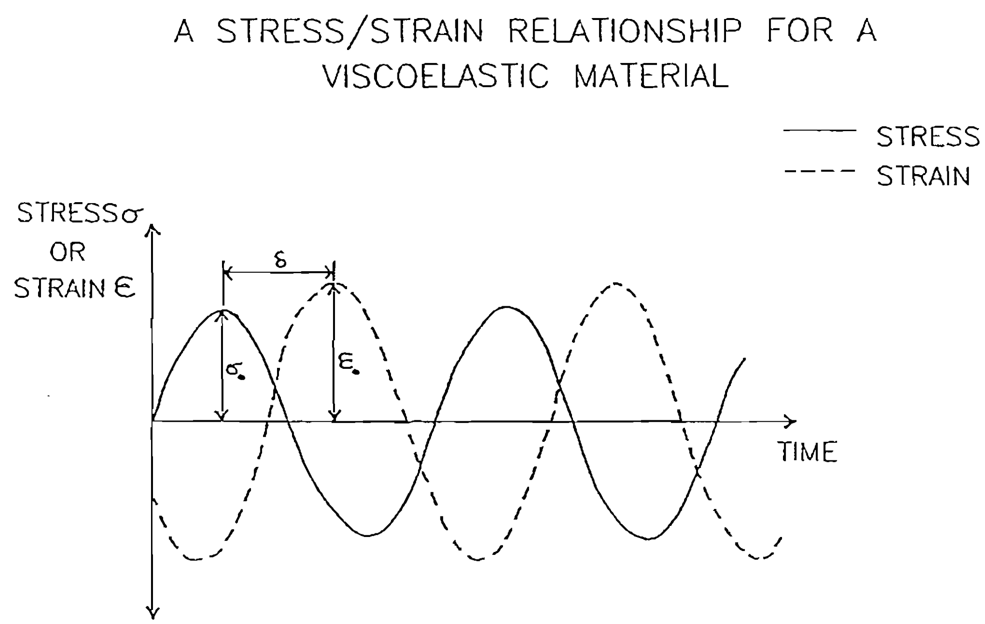
From these expression we can define the in-phase and out-of-phase components of the Young's modulus as:

$$E' = |E| \cos\delta \qquad E'' = |E| \sin\delta$$

These are termed the storage and loss modulus, respectively. The storage modulus is a measure of the stiffness of the material. The ratio of these two quantities is equal to tanδ, which is an important measure of the strength of a relaxation in a material. We will be most concerned in this report with changes in the storage modulus.

The results of the DMA analysis show evidence of two counteracting effects. Firstly, an increase in the temperature of a viscoelastic material usually results in a decrease in modulus. On the other hand the sample loses water during the DMA run, and therefore the modulus or stiffness increases. It is important to keep in mind that the loss of water occurs relatively rapidly compared to the processes we observe in this section. Therefore the changes in modulus observed during isothermal experiments largely reflect changes in properties of the individual components themselves. In addition we believe that due to the small size of the samples the temperature of the sample is rapidly equilibrated. Experimental evidence is presented to support this conjecture.

Figure 1. The response of a viscoelastic material to an applied oscillating stress.



Thermo-Gravimetric Analysis (TGA) is a method for measuring the weight loss of a material on heating. The sample is heated on a sensitive balance inside a furnace. The technique therefore provides a measure of the rate and extent of water loss on heating.

2. Materials and Methods

The samples used were a fresh sample of green *Pinus caribaea* morelet var. hondurensis barett & golfari (WW-A), a sample retained at 4 °C for one month (WW-B), and a sample of kiln-dried timber (160 °C) kept at ambient conditions for one month (DW).

DMA analysis was performed on a Perkin-Elmer DMA-7, using the three-point bending apparatus. The sample size was 20mmx3mmx0.5mm. A frequency of 1 Hz was used unless otherwise stated. The sample was enclosed in a variable temperature chamber, and the sample heated by a furnace. A stream of He gas was passed through the chamber at all times.

TGA measurements were made on a Perkin-Elmer TGA-7. Samples of mass 1-30 mg (nominal standard mass = 15 mg) were placed into platinum pans and heated under pure air flowing at 40 cm^2/min. Measurements were made wither at constant temperature (isothermal), or with a programmed temperature regime.

3. Results and Discussion

DMA

The dynamic response of a sample of green timber (WW-A) was studied during heating to 200 °C at 20 °C/min. At this heating rate the behaviour of the wood under a strain will be influenced both by dynamic processes and by transport processes (i.e. drying). Figure 2 shows the change in modulus during the first heating run. The modulus increases during heating, due partially to loss of water and stiffening of the matrix. A second sample was heated to 150 °C for 20 minutes (to constant mass) and cooled to room temperature. The subsequent DMA analysis of this sample (Figure 3) shows a decrease in modulus with increasing temperature, as expected for a viscoelastic material.

Figure 2. The change in modulus during the first heating run of a sample of kiln-diren wood.

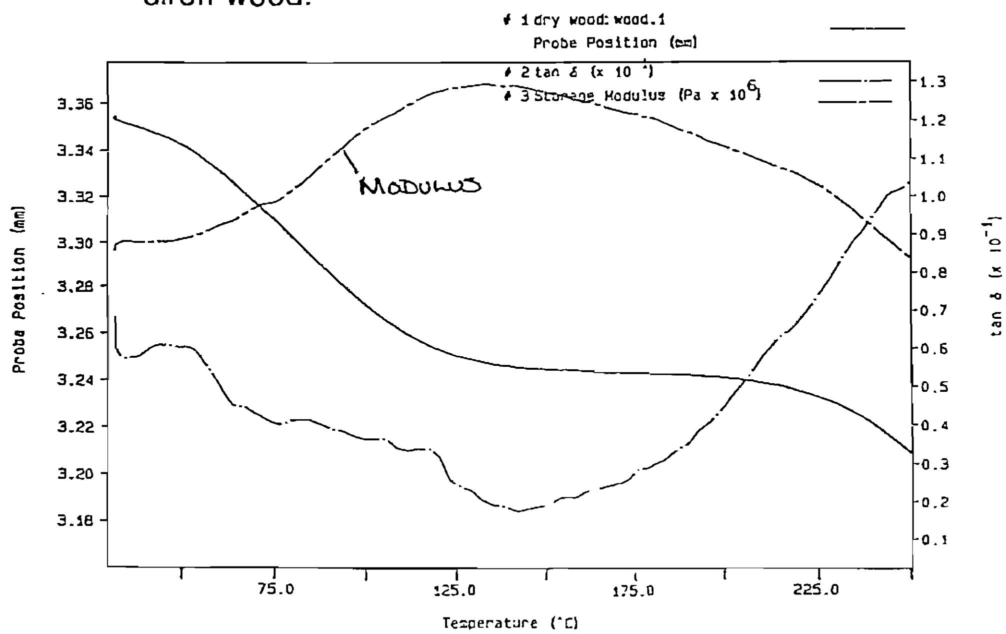
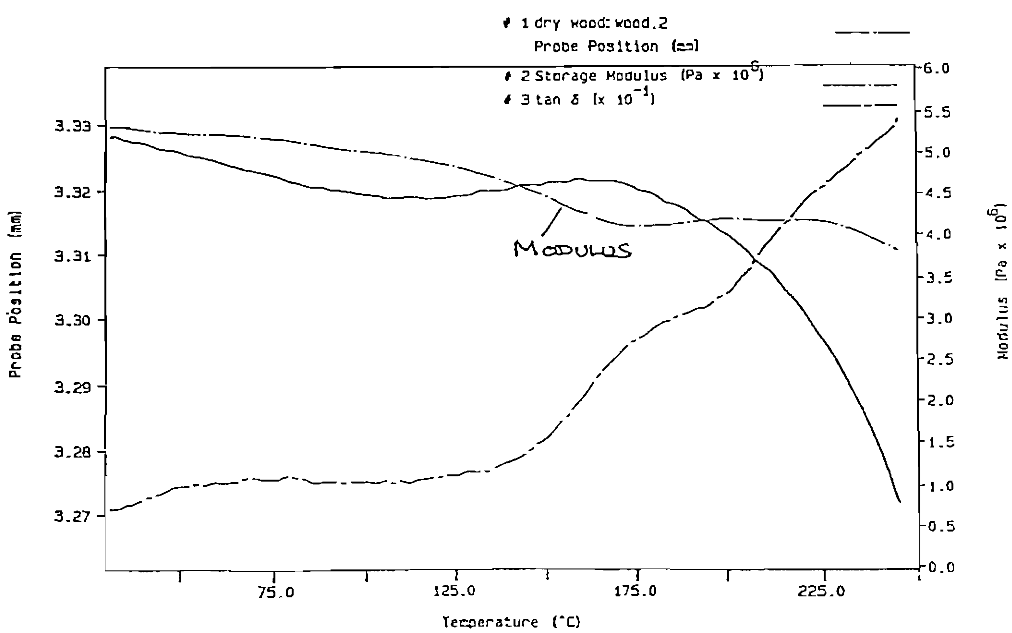
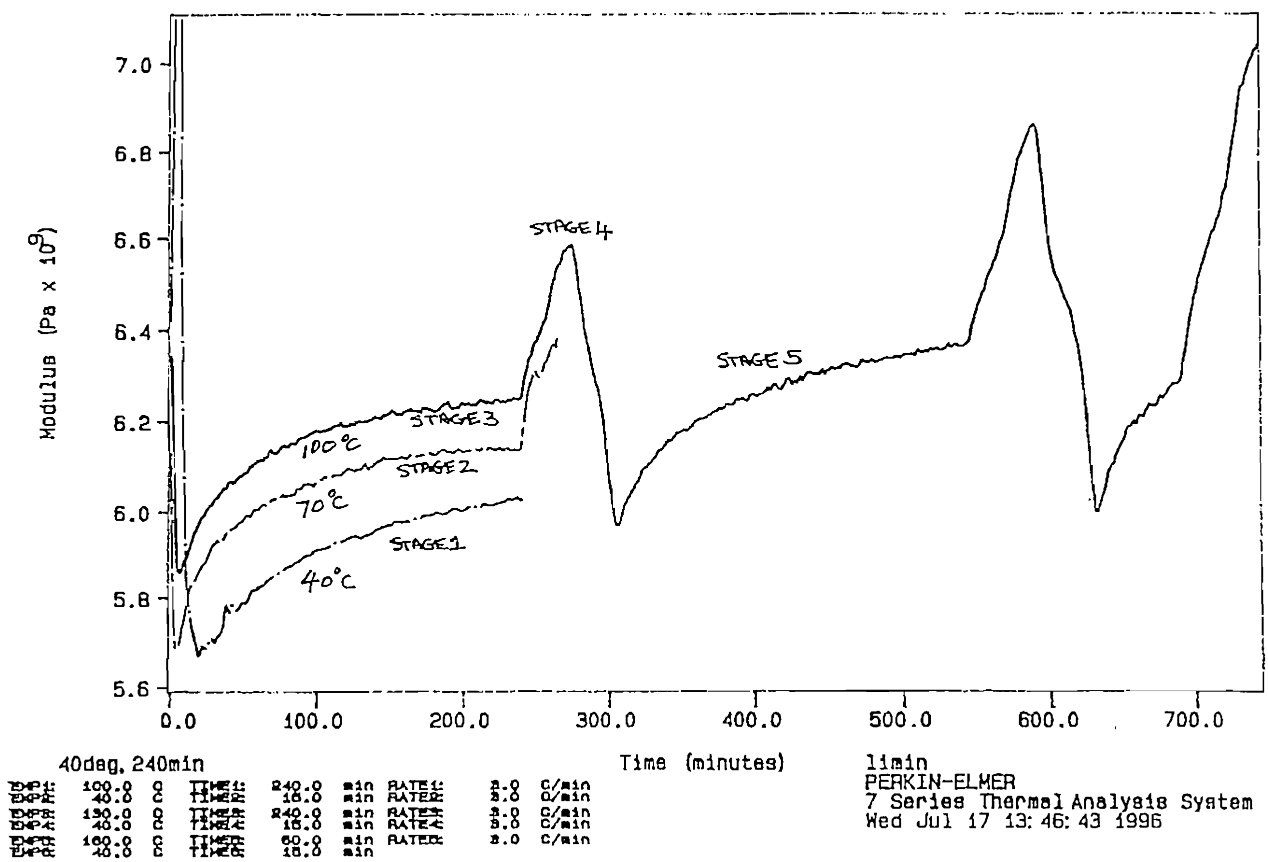


Figure 3. The change in modulus during the first heating run of a sample of kiln-diren wood previously heated to 150 °C for 20 minutes.



As suggested above, the observed change in modulus during initial heating is due to loss of water, and also to changes in modulus of the material not associated with the transport process. TGA analyses have shown that during isothermal heating the mass of a sample has equilibrated after less than 10 minutes. We have devised several experiments to try to separate the effects of water loss and changes in bulk modulus. Figure 4 shows the results of the first of these experiments. The modulus of a sample of WW-B has been followed during the following heating regime. Firstly, the sample was heated to 40 °C and the modulus observed over 240 minutes (stage 1). The modulus increases in an approximately exponential manner by ca. 6-7 % over this time period. Recall that the TGA results had shown that the mass of the sample had equilibrated in less than 10 minutes. Therefore the increase in modulus cannot be due to loss of water from the sample. Possible explanations for the increase in modulus would include a) a redistribution of the water throughout the sample, or b) a change in the packing of one of the viscoelastic components of the wood, i.e. the lignin or the hemi-cellulose. The temperatures considered are far too low to affect the dynamics of the cellulose fibre themselves.

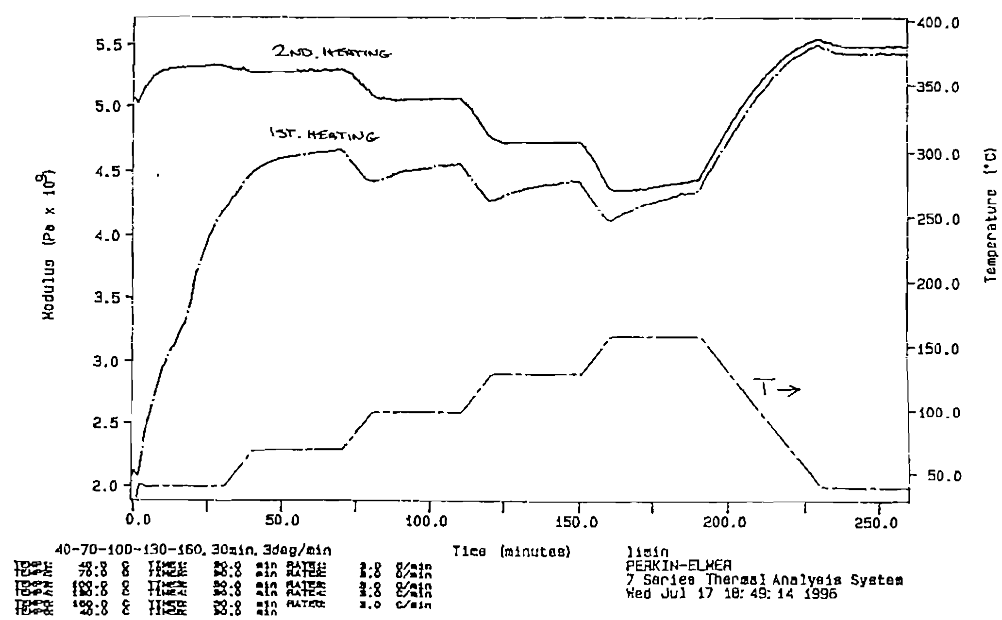
Figure 4. Modulus of WW-B taken through the following heating regime: stage 1 - heated at 40 °C for 240 mins, stage 2 - 70 °C for 240 mins, stage 3 - 100 °C for 240 mins, stage 4 - cooled to 40 °C then reheated to 100 °C, stage 5 - held at 100 °C for 240 mins. The cooling heating cycle was then repeated.



This sample was subsequently heated to 70 °C, and then 100 °C (stages 2 and 3 of Figure 4). A similar increase in modulus was observed of 6-7 %, over a time scale much longer than the time taken for the mass to equilibrate at these temperatures. To further underline the importance of the changes in the modulus of the matrix, the sample was cooled (stage 4) then reheated to 100 °C, and the increase in modulus again followed with time (stage 5). The mass of the sample did not change during this time. In addition this experiment would also be less sensitive to a redistribution of water throughout the material (although this effect is not ruled out). It appears therefore that heating to a higher temperature results initially in a decrease in modulus, followed by an increase over several hours.

Another phenomenon observed was that heating to an elevated temperature resulted in a change of the modulus, but that subsequent annealing at a lower temperature did not result in the above-noted increase in modulus with time. Figure 5 demonstrates this effect. A sample of fresh green timber (WW-A) was heated in stages to 160 °C, over a period of 200 minutes. The temperature profile used in this experiment is shown in Figure 5 as the double dashed line. The modulus is shown as the dot-dashed line. The modulus is seen to decrease initially as the temperature is raised, and then increases with time at each temperature. However, when the same sample is cooled and taken through the same temperature run (solid line) the modulus decreases initially on an increase in temperature, and does not increase significantly on annealing at each temperature until the maximum temperature is reached. This behaviour is indicative of the phenomenon of physical aging, in which the structure of a glassy polymer can be affected by heating at temperatures below the glass transition temperature. This heating results in a densification of the glassy material, and an increase in glass transition temperature.

Figure 5. Modulus of a sample of fresh green timber (WW-A) heated and annealed at progressively higher temperatures up to 160 °C (dash dot line). The same sample was cooled and passed through the same temperature regime and the modulus recorded (solid line). The temperature regime used is shown as the double dashed line.

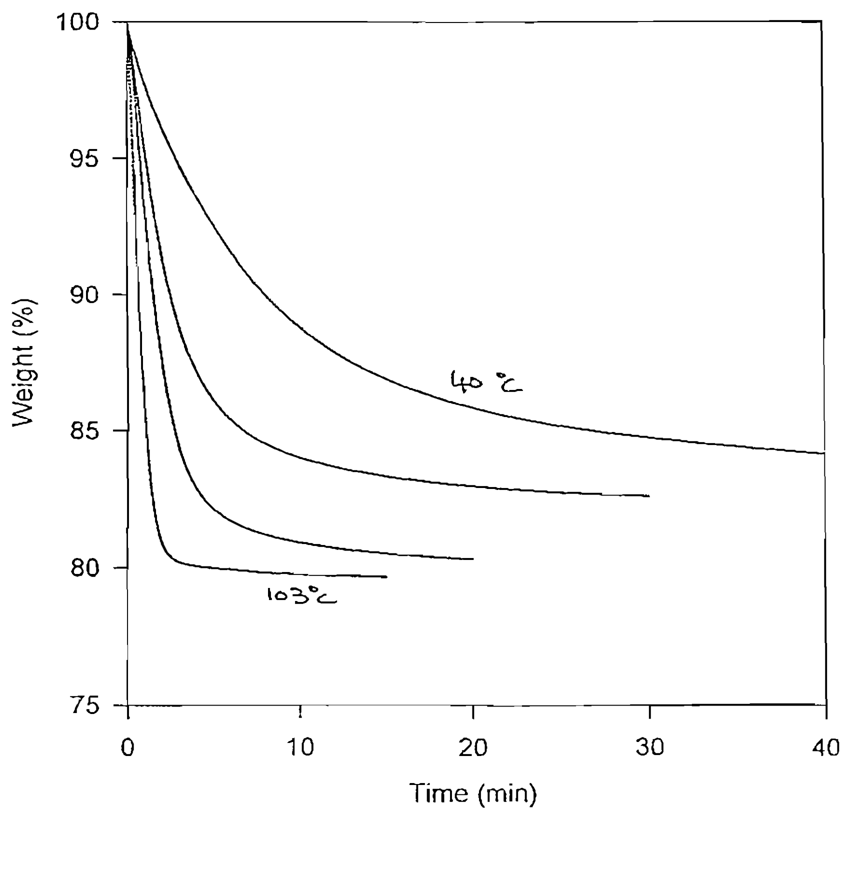


TGA

Figure 6 shows the weight of a sample equilibrated at 4 °C (WW-B) sample after heating at constant temperatures of 40, 60, 80 and 103 °C. Firstly the rate of water loss increases rapidly on increasing temperatures, and the final mass loss increases with increasing temperature. This is consistent with previous observations, which have been interpreted as indicating that heating to successively higher temperatures leads to loss of water in continually smaller pores. At moderate temperatures (> 100 °C) the mass of the sample has equilibrated after less than five minutes. This has important implications for the DMA analyses above, which uses a sample of similar size. An estimate of the activation energy of the processes occurring can be obtained from a plot of the time to loss of half of the maximum mass loss, as a function of inverse temperature. This plot is linear, and indicates an activation energy of 38 kJ/mol.

The effect of varying the heating rate on the loss of water is very dramatic as seen in Figure 7. Measurements were made on identical samples heated at rates of 2, 5, 10 and 15 °C/min. Two observations can be made initially: 1) the temperature at which half of the water has been lost moves to lower temperatures at lower heating rates, and 2) at higher rates the final mass of water lost is increased, for example 21% of water is lost with a heating rate of 2 °C/min, while 31% of water is lost for a heating rate of 15 °C/min.

Figure 6. Mass of identical samples of conditioned timber (WW-B) as a function of time at temperatures of 40, 60, 80 and 103 °C (Isothermal TGA). The slower decays are observed at lower temperatures.



As a measure of the rate of water loss, the time for loss of half of the maximum mass loss has been measured from Figure 7. This time is 4.8 minutes at 2 °C/min, 4.0 at 5 °C/min, 3.6 minutes at 10 °C/min and 3.1 minutes at 15 °C/min. This indicates that the apparent activation energy for loss of water is lower at higher scan rates.

Figure 7 Mass of identical samples of conditioned timber (WW-B) on heating to 250 °C, at heating rates of 2, 5, 10 and 15 °C/min.

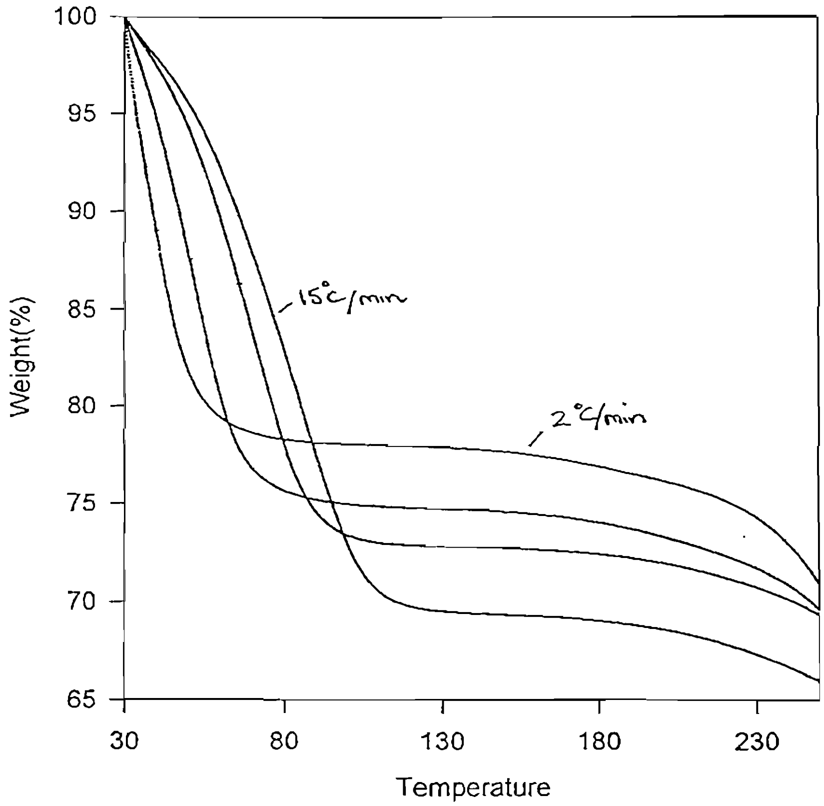
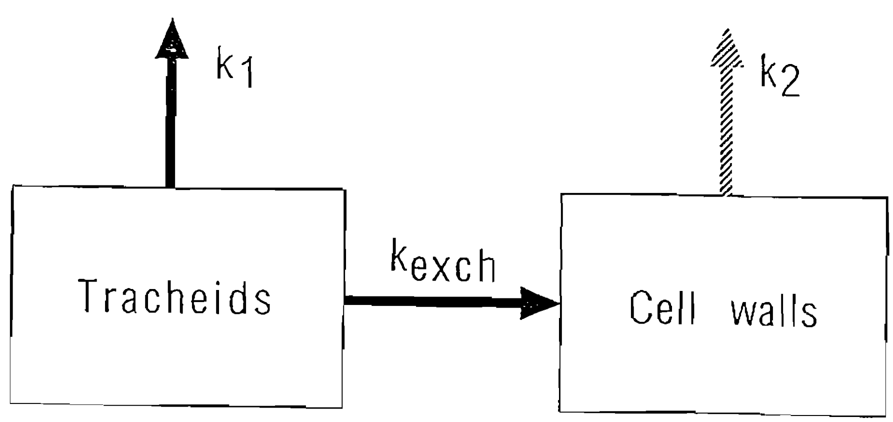


Figure 8 Simple model for the transport of water in soft wood derived from the data in Figure 3.23. Note that $k_1 > k_{exch} >> k_2$.



A simple model for the observation of increased weight loss at higher scan is suggested. The water is partitioned into two reservoirs (Figure 8), one with high rate of water loss (k_1), and a second with a much lower rate of water loss (k_2). Water can pass from the first to the second reservoir at an intermediate rate (k_{exch}). In physical terms the reservoir which loses water at a rate k_1 is water in tracheids. The second reservoir (k_2) is water in cell walls. On heating two competing processes occur, namely the loss of water from the tracheids directly, and secondly diffusion of water from within the tracheids into the cell wall. Diffusion of the water out of the cell walls is comparatively slow. Therefore at a slow scan rate, there is sufficient time for diffusion into the cell walls to occur, while at a higher scan rate most of the water is lost directly from the tracheids, and so therefore the final weight loss increases with increasing scan rate. It is likely that this mechanism could be confirmed by NMR spectroscopy and NMR Imaging.

4. Conclusions

DMA

DMA analysis has demonstrated the effects of both transport of water, and changes in the structure of the viscoelastic components of the wood. At short times, or with high scan rates) the loss of water leads to an increase in the modulus of the sample. The effects of loss of water appear to cease after less than 10 minutes. Over longer periods of time the modulus of the sample increases continually. Evidence is presented that this is a process of physical aging, in which the glass transition temperature is increased by prolonged annealing below Tg. Subsequent heating to below these annealing temperatures does not lead to increases in modulus.

TGA

The rate of loss of water for WW-B (conditioned in the refrigerator) increases with increasing heating temperatures with an activation energy of 38 kJ/mol. The total mass loss increases with increasing temperature consistent with previous measurements. In experiments where the mass was measured with continual heating the total mass loss, and the rate of loss of water depends on the heating rate. A simple two reservoir model for the states of water has been suggested. The two reservoirs consist of water in tracheids, and water in cell walls.

Inconsistent results were obtained with green timber (WW-A), due to very rapid loss of water during loading of the sample into the TGA instrument. Much greater consistency was obtained for sample equilibrated at 4 °C (WW-B). These latter samples lose 20-30% mass on heating. Fresh samples of green timber (WW-A) lose ca. 50% of mass on heating. Samples of dry (DW) lose ca. 10% mass on heating.

ESTIMATION OF THE MOISTURE CONDITION OF TIMBER FRAMEWORK IN AUSTRALIAN HOUSES

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ABSTRACT

Results from three different surveys of microclimate in the building envelopes of Australian houses are presented. Eighteen houses have been surveyed in tropical, subtropical, temperate and cold climates. In all three surveys, surface equilibrium moisture content (SEMC) is calculated from air temperature and relative humidity (RH), while in the third survey electronic readings and mass change measurements of equilibrium moisture content (EMC) have been made. The implications of the EMC and SEMC values for the growth of wood decay fungi and degradation of melamine-urea-formaldehyde (MUF) adhesives is discussed. Building science factors that promote the observed microclimates are outlined.

INTRODUCTION

The moisture content of timber is a critical factor defining the onset of a number of degradation processes involving either timber or timber connectors. These processes include fungal growth and mechano-sorptive creep for timbers, glue degradation and corrosion of connectors. However, in Australia relatively little work has been conducted on the microclimate in houses and the implications of this microclimate to timber durability. At the last Forest Products Conference, the authors (Cole 1993) presented a paper defining the equilibrium moisture content (EMC) in timber members in wall cavities of houses in Melbourne, Brisbane and Darwin. Since that time, the authors have undertaken a number of surveys of climate and material response and are able to present a more detailed analysis of conditions not only in wall cavities but also in subfloors, wall cavities, and roof spaces.

SOURCES OF DATA

The data in this paper is derived from the literature as well as from three surveys undertaken by CSIRO BCE. Survey 1, which is documented in Cole (1993; 1994), was undertaken in 1989–1991 and concentrated on determining the microclimate in wall cavities. Survey 2, which is partially documented in Cole *et al.* (1996), was undertaken in 1993–1996 and concentrated on studying the microclimate in roof spaces and wall cavities in slab-on-ground houses. Survey 3, which commenced in November 1995, concentrates on the microclimate in subfloors and wall cavities of houses with suspended timber floors. EMC was not measured in Surveys 1 or 2 and thus can only be estimated from microclimatic data, while direct measurements of EMC on in-situ timber and on sample sticks are being made in Survey 3. In Table 1 some characteristics of the houses surveyed are given. The period (in months and years) of monitoring is given which, in the case of Survey 3 which is still being undertaken, is the period from which data has been analysed. In the case of the Darwin, Cairns and Innisfail houses, sarking and insulation were both placed at the roof level and sarking was placed in the wall cavities. In the

TABLE 1. CHARACTERISTICS OF SURVEYED HOUSES

Survey	Location	No.	Period	Type	Foundation	Ventilation	Crawl space (m)
1	Melbourne	1	5/89–5/91	Brick veneer	Slab on ground	Vents, standard*	
1	Brisbane (Sinamon Park)	1	5/89–5/91	Brick veneer	Slab on ground	Weep holes	
1	Darwin	1	5/89–5/91	Brick veneer	Slab on ground	Weep holes	
2	Cairns area	3	12/93–12/95	Brick veneer	Slab on ground	Weep holes	
2	Sunshine Coast	2	5/94–5/96	Brick veneer	Slab on ground	Weep holes	
2	Sunshine Coast	1	5/94–5/96	Brick veneer	Slab on ground	Vents, standard	
2	Brisbane	2	2/94–2/96	Brick veneer	Slab on ground	Weep holes	
3	Melbourne	1	2/96–5/96	Solid brick	Suspended timber floor on brick piers	Vents, standard	0.5
3	Mt Buller	1	8/95–5/96	Masonry block	Suspended timber floor on block piers	Vents, standard	1.5
3	Narrandera	1	8/95–8/96	Brick veneer	Suspended particleboard floor onbrick piers	Vents, greater than standard	0.5
3	Sydney (Epping)	1	10/95–8/96	Timber, brick clad	Suspended timber floor on brick piers	Vents, mainly blocked	0.4
3	Brisbane(The Gap)	1	5/96–8/96	Brick veneer	Suspended plywood floor on brick piers	Weep holes	0.4–2.0
3	Innisfail	1	12/95–7/96	Brick veneer	Suspended timber floor on block walls/steel posts	Weep holes	0.5–2.0
3	Innisfail	1	12/95–7/96	Queenslander	Timber floor on timber posts	Open subfloor	1.5

* Vents in accordance with normal practice for locality.

Sunshine Coast and Brisbane houses, sarking was placed at the roof level without insulation and sarking was in general placed in the wall cavities, although the 'The Gap' Brisbane house was not sarked. In the case of the Melbourne house, both walls and roof space (at the ceiling level) were insulated, while only the walls were sarked. In the case of the Sydney house, neither insulation nor sarking was used. As is evident from the table, over the three surveys 18 houses have been investigated in eight centres.

ANALYSIS

Building Envelope

In Tables 2 and 3 the available information relating to EMC of timbers in the building envelope is presented. Data in Table 2 has been derived from on-site measurements, while the data in Table 3 is estimated from microclimatic data. In these tables the term 'restricted' is applied to indicate any part of the subfloor where cross-flow ventilation is restricted and thus drying rates may be limited and moisture problems may arise. In the same context 'normal' refers to the condition where cross-flow ventilation is effective.

TABLE 2. MEASURED EMC IN BUILDING ENVELOPES

Location	Position	Wood type	EMC range (%)
New Zealand	Subfloor joist/beams	Radiata	14–23 (outliers up to 25)
Brisbane	Subfloor joists/beams	Black butt	14–17; 17–19 restricted
Innisfail	Subfloor joists/beams	Cypress pine	12–16; 20 restricted
Narrandera	Subfloor joists/beams	Black butt	7–10
Melbourne	Subfloor joists/beams	Victorian ash	14–18; 18–23 restricted
Mt Buller	Subfloor joists/beams	Victorian ash	14–18
Perth	Subfloor joists.beams	Not identified	<10
Sydney	Subfloor joists/beams	Black butt	<16; 18 restricted

TABLE 3. ESTIMATES OF EMC FROM CLIMATE STUDIES

Location	Position	SEMC range (%)	SEMC range (%) restricted
Brisbane	Subfloor joists/beams	10–17	14–18
Innisfail	Subfloor joists/beams	14–24	10–30
Mt Buller	Subfloor joists/beams	10–24	14–24
Sydney	Subfloor joists/beams	6–23	6–28
Sydney	Wall cavities	6–24	
Darwin	Wall cavities	10–22	
Cairns	Wall cavities	8–24	
Innisfail	Wall cavities	6–30	
Brisbane/Sunshine Coast	Wall cavities	8–22	
Melbourne	Wall cavities	10–21	
Cairns	Roof space	8–18	
Brisbane/Sunshine Coast	Roof space	6–17	
Cairns	Above sarking	4–20	
Brisbane/Sunshine Coast	Above sarking	4–16	

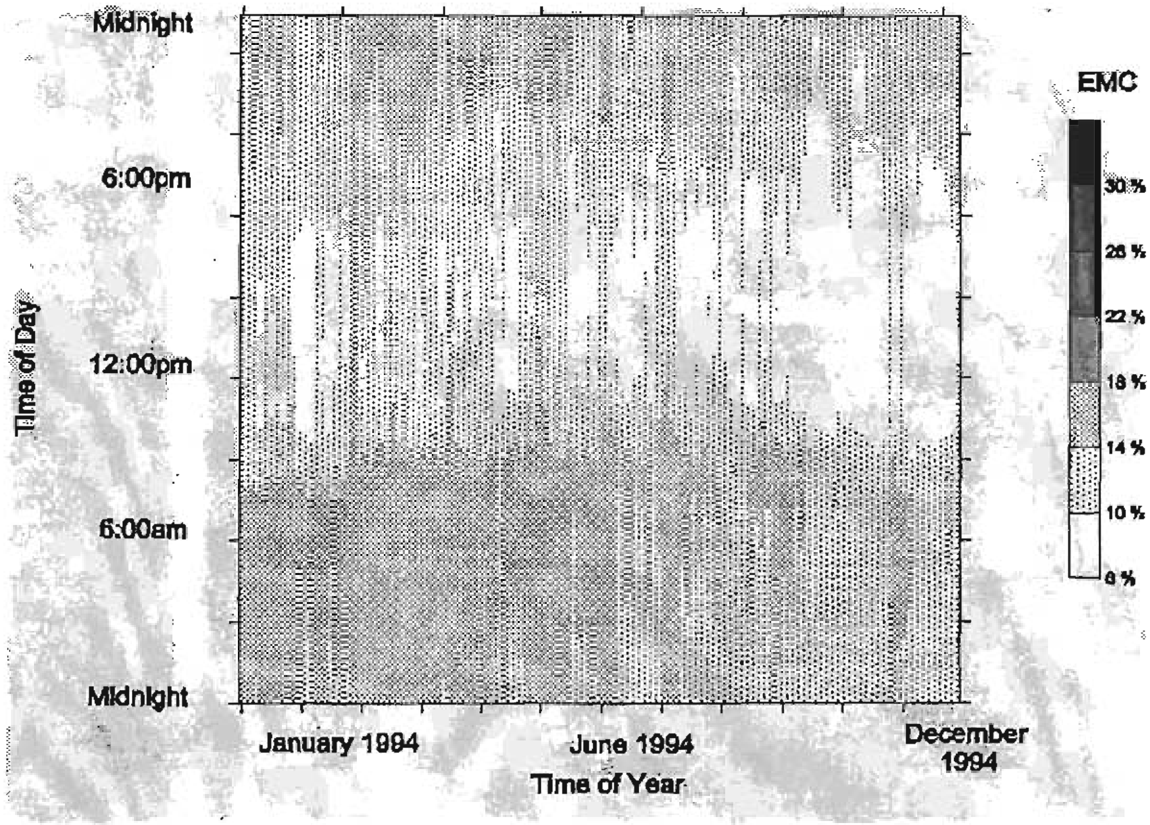

Fig. 2. Seasonal and daily variation in SEMC in roof space at Edmonton (Cairns area).

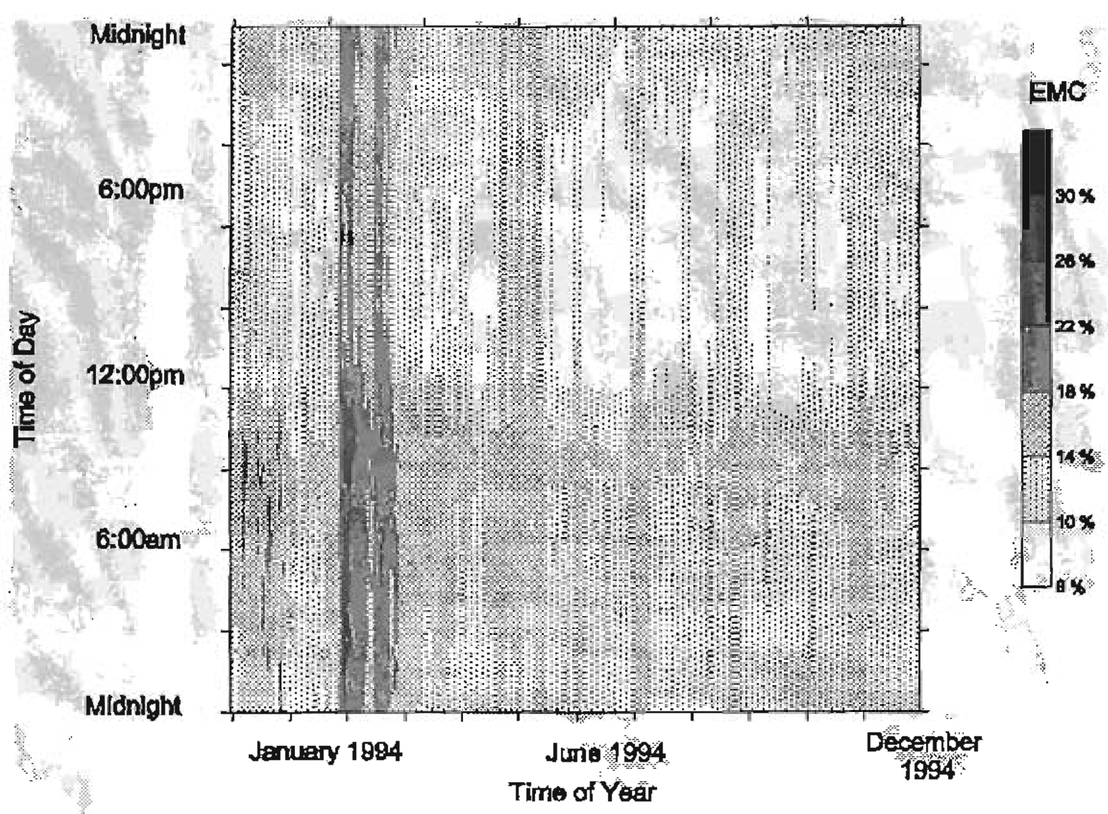

Fig. 3. Seasonal and daily variation in SEMC in a north wall cavity at Edmonton (Cairns area).

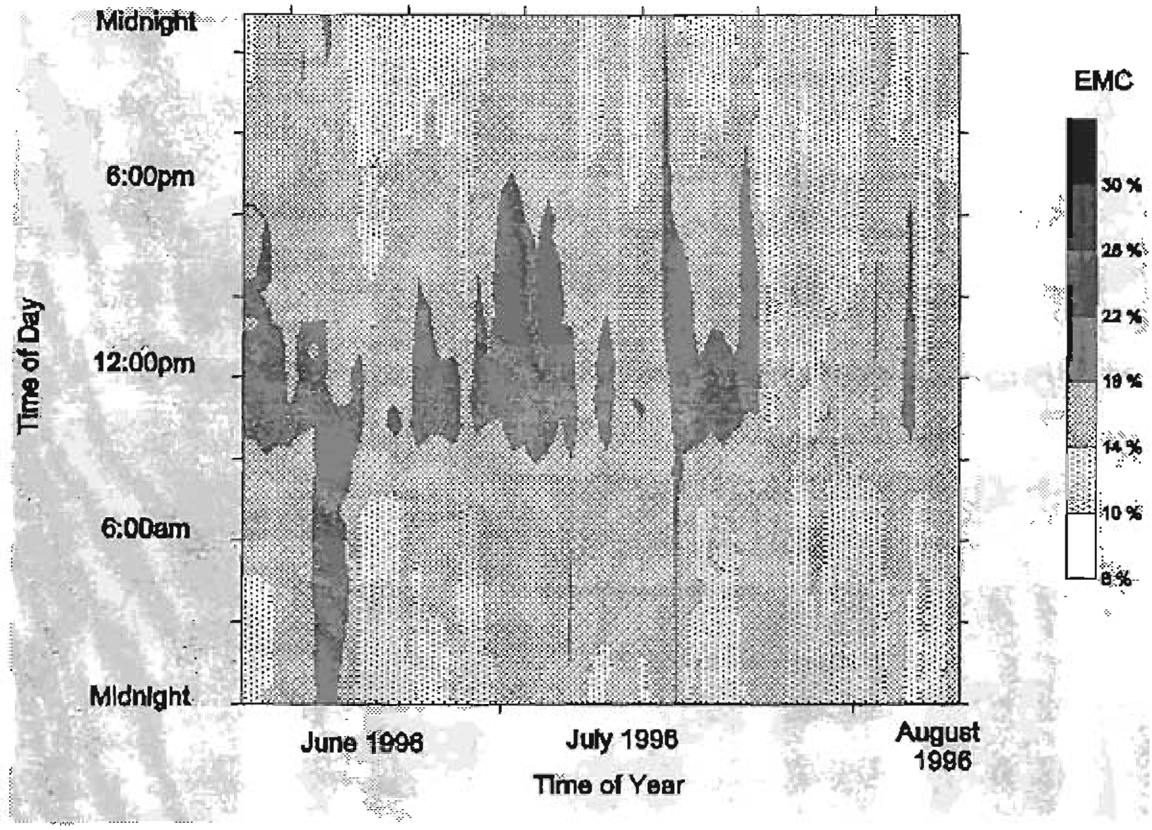

Fig. 4. Seasonal and daily variation in SEMC in a south wall cavity at The Gap (Brisbane).

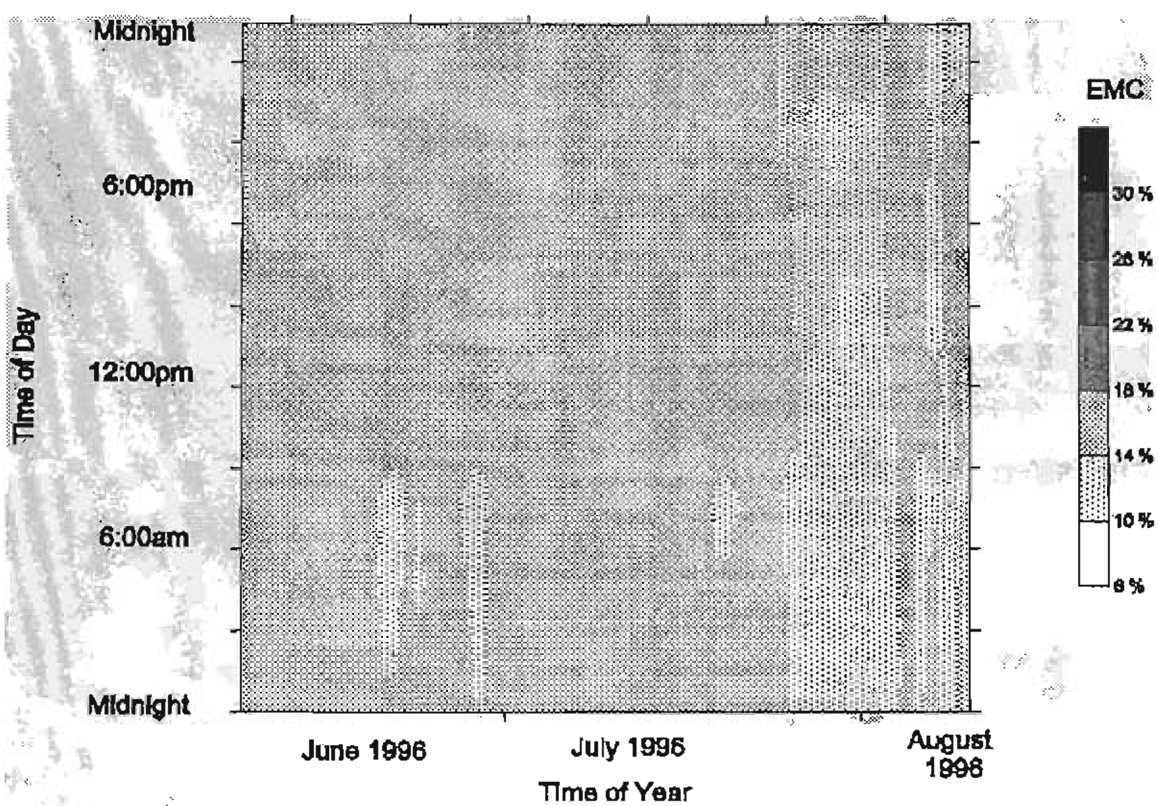

Fig. 5. Seasonal and daily variation in SEMC in a subfloor at The Gap (Brisbane).

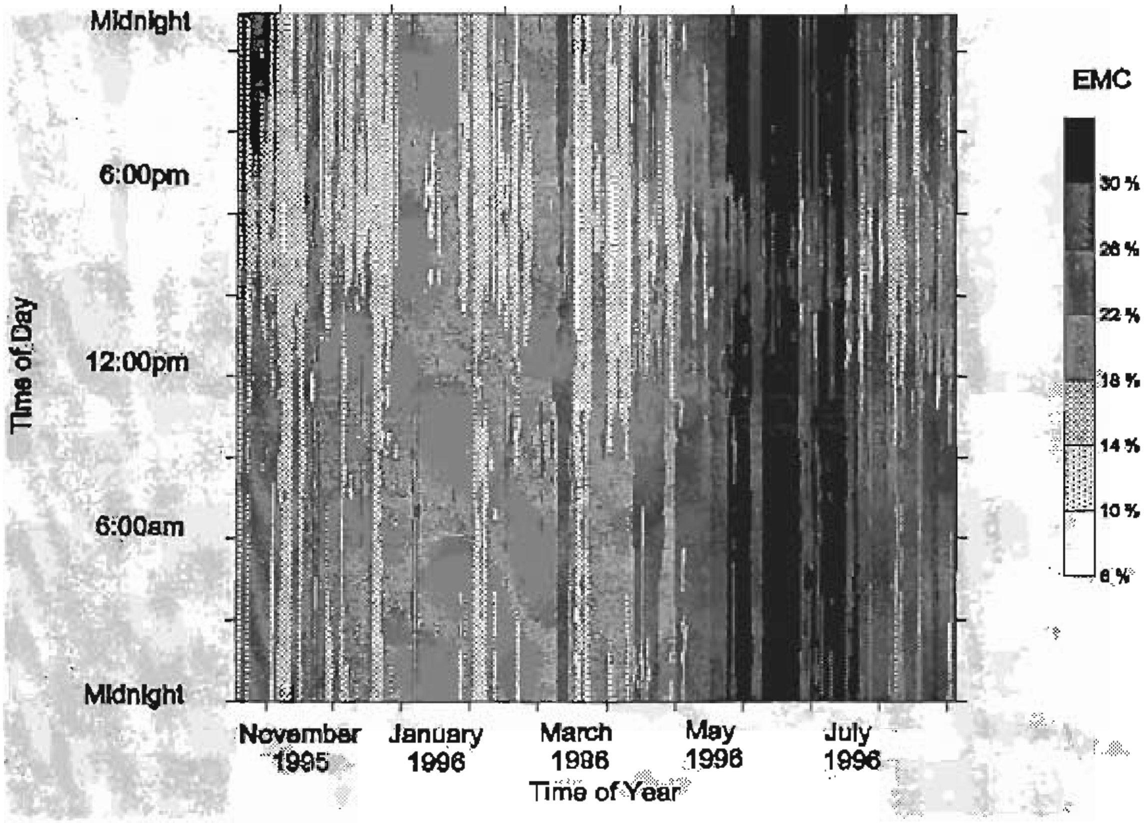

Fig. 6. Seasonal and daily variation in SEMC in a subfloor at Epping (Sydney).

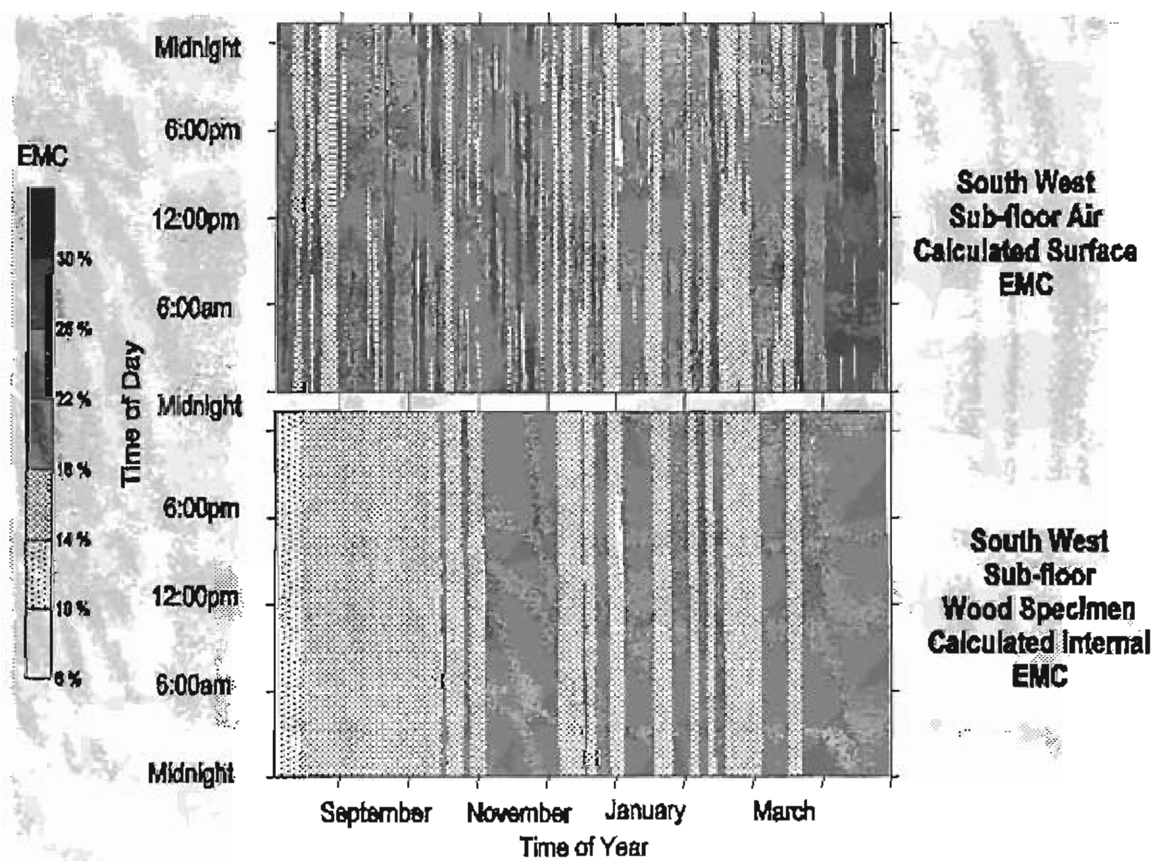

Fig. 7. Seasonal and daily variation in SEMC in a subfloor and EMC in a radiata pine block in a subfloor at Mt Buller.

The nucleation and growth of fungi are expected to be controlled by EMC, so that fungi will form if the EMC exceeds fibre saturation while fungal growth will cease if the EMC is lower than 18%. Thus, the results presented in Tables 3 & 4 and Figs 2–7 indicate significant periods of fungal growth can occur in subfloors, particularly those in high rainfall areas, mountainous areas or with poor ventilation. In houses in which subfloors were well ventilated and the climate was not excessive (e.g. refer to Fig. 5), conditions for fungal growth did not occur. Conditions appeared to be more severe in wall cavities with respect to subfloors, so that conditions suitable for fungal growth occurred in all locations studied except the inland site. It is also notable that conditions suitable for fungal formation were only observed in a wall cavity in Innisfail. Interestingly fungal growth was detected on sticks of timber placed in the subfloor in an area of restricted ventilation in Epping (Sydney).

Building Science Factors Affecting Moisture Content

As indicated in Cole *et al.* (1996), wall cavities have a distinct microclimate which is influenced by temperature differential across the building. This study found that in houses in subtropical and tropical environments, the daily temperature cycle in a wall cavity is in general lagged with respect to that exterior to the house. Thus, while the mean temperature in a wall cavity may be higher than that exterior to the house, in certain seasons the wall cavity temperature in the morning may be appreciably lower than that exterior to the house. This temperature difference could promote condensation and/or high humidity in the wall cavity because, as warm moist air from the exterior infiltrates into the wall cavities, it would cool and decrease its capacity to hold water. Such high humidities would be expected to raise surface EMC. In fact this effect is apparent in wall cavities in Edmonton and The Gap as presented in Figs 3 and 4. The maximum SEMC occurs mid-morning (around 9 and 10 a.m.), with the minimum occurring around 6 p.m. at Edmonton, while the maximum SEMC occurs around midday and the minimum around 9 p.m. at The Gap. In contrast, the maximum exterior RH occurs in early morning (5–6 a.m.) and minimum around midday. A second factor evident in wall cavities is that once moist conditions have developed, they may persist for significant periods of time so that the daily cycle is overridden.

The dampening of the daily cycle is even more evident in the subfloor temporal plots, with the daily cycle being scarcely evident at The Gap (Fig. 5) and Mt Buller (Fig. 7). Figure 6, which presents the subfloor at Epping, indicates a daily cycle similar to that observed for tropical wall cavities. However, as indicated before, when damp conditions set in they override the daily cycles. More research is needed to determine the exact significance of the dominance of damp conditions over the daily cycle, however, it does indicate the limited influence of external conditions. As the external air has a strong daily cycle in RH (or EMC), the fact that this cycle is absent in the subfloor indicates that the extent of air exchange with the exterior is limited, implying that ventilation is not effective.

In Fig. 7 the conditions within a block of radiata pine are compared with the estimated SEMC. It is evident that patterns are very similar although variations at the centre of the block are damped compared to those at the surface. The relatively low values of EMC in the wood block at the start of the monitoring period may reflect the period required for the block to respond to the changed conditions. It is notable that EMC values in excess of 18% occur at mid-section of this block indicating that degradation under these conditions would not be restricted to the surface.

CONCLUSIONS

This paper summarises the results of three surveys of houses (in total 18 houses) in eight centres covering the climatic zones of the eastern part of Australia. Estimations of EMC from climatic data have been made which have been partially validated against measurements. Nevertheless some uncertainty does exist concerning the validity of the estimation, and thus the conclusions set out below are best regarded as preliminary.

- SEMC values in excess of 18% may occur in subfloors and wall cavities of houses sited in areas with particularly high rainfall, or cold conditions or in association with sub-standard ventilation.
- SEMC values exceeding 18% may not occur in well-ventilated subfloors in zones not subjected to severe weather conditions.
- SEMC values exceeding 18% have been observed in the wall cavities of houses of all centres monitored except inland centres.

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Correlated Microscopy Studies of the Distortion of Kiln Dried Softwood

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The origins of the distortions of kiln dried juvenile softwoods are not well established. Spring and bow of the timber may be explained in terms of the differential stresses and dimensional changes set up by the essential heterogeneity of the timber across a log and the reequilibration with atmospheric conditions following overdrying in the kiln drying process. In associated studies (Dong *et al.*, 1996, *these proceedings*) have established that the water distribution in timber following drying is not uniform or necessarily in equilibrium with external atmospheric conditions and that considerable redistribution must take place subsequent to removal from the kiln. The exact mechanisms that produce these distortion are not however well understood, particulary in regard to the mechanism by which changes in the moisture distribution produce differential stresses resulting in distortion. A better understanding of the mechanisms involved at the microstructural, ultrastructural and molecular structural levels is a necessary step to identify potential means to minimise distortions and the subsequent losses to the industry through wastage. An understanding of the mechanisms of twist in these timbers is a major objective in these studies although informaton relevant to the mechanisms underlying the other distortions can be expected to be obtained.

Timber is a complex heterogeneous composite, primarily of cellulose, hemicellulose and lignin. Its behaviour is not simply understood by studying the properties at any one of these levels. To establish mechanisms, it is necessary to follow the chemical and dimensional changes introduced by changing moisture level through from the molecular level to the dimensional changes occurring at the ultrastructural and cellular microstructural levels and ultimately at the macroscopic level. To this end, a number of diffraction and microscopical studies are being employed to identify these mechanisms. The diffraction methods range through X-ray diffraction (Reitveld, texture goniometry and small angle X-ray scattering (SAXS), electron diffraction, small angle neutron scattering (SANS) and diffraction, optical diffraction, each offering information at overlapping and increasing dimensional scales. These are complemented by corresponding microscopy studies in the transmission electron microscope (TEM), environmental SEM (ESEM) and scanning confocal microscope (SCM) to measure changes at these levels and aid with the interpretation of the diffraction information.

Reitveld analysis of X-ray diffraction data obtained from 5° to 75° in 0.05° steps using graphite monochromated Cu K_α and Co K_α radiation provides information on the changes

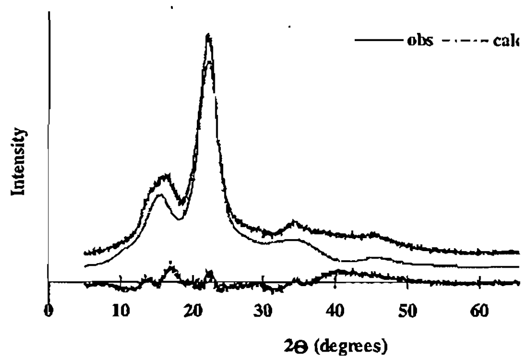


Figure 1 Dried Hoop pine grain parallel to beam

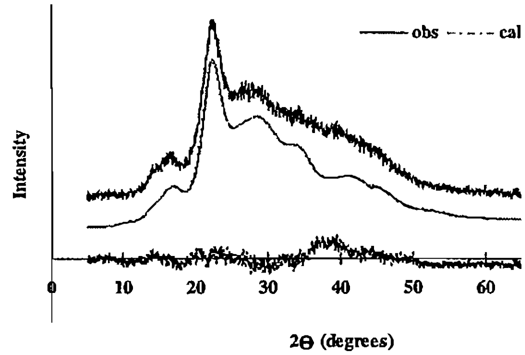


Figure 2 Dried Hoop pine grain parallel to the beam following rewetting

occuring at the molecular level, primarily in the cellulose component of the timber structure. Reitveld analysis results to date have shown disorder in the structure of green timber. During the drying process this disorder is irreversibly reduced through some crystallisation process. Dried timber exhibits less disorder, with three components, a rod like disorder (cellulose polymer), a layer like disorder (sheet like galactomannan structures, Marchessault *et al.* 1979) and a poorly structured polysaccharide component. The layer disorder is thought to result from the hemicellulose component which shares similar glucoside structural units to the cellulose component. Rewetting of the dried samples produce similar diffraction patterns with the addition of a scattering contribution by water illustrated in Figure 1 and 2. A summary of the Reitveld structural factors for each component is given in Table 1. The scale factors indicate the relative contribution of each component to the spectrum and the size factors indicate the relative sizes of the structural components.

Table 1: Summary of structural parameters derived from Rietveld analyses of wet and dry Caribbean pine woods.

	Wet		**Dry**	
	Scale Factor	**Size**	**Scale Factor**	**Size**
Rod	0.00512	25	0.00132	32
Layer	0.00864	52	0.04195	21
Cellulose	0.00173	18	0.00004	54
Polysaccharide	0.05480	12	-	-
Water	-	-	0.17897	11

In the texture analysis, a single diffraction peak from the cellulose is selected with the timber sample initially aligned with the grain parallel to the direction of the incident X-ray beam incident X-ray beam. The sample is then tilted about the direction of incidence and rotated relative to the incident beam. The resulting data is a polar plot showing the orientation distribution of the planes in the crystal structure which correspond to the selected peak.

X-ray texture plots collected with the incident beam parallel to the grain of the timber from the (040) plane of cellulose are shown in Figures 3 and 4 for dry and rewetted juvenile Caribbean pine (*pinus caribaea*) respectively. These planes correspond to a diffraction vector in the direction of the polymer chains in the microfibril. The monoclinic unit cell structure and orientation for cellulose (reported by Meyer et al 1929, 1937a and b quoted in Otto and Spurlin, 1954) with the monoclinic axis as b along the fibre has been adopted in this discussion rather the orientation used by Gardner and Blackwell, 1974 discussed by Okamura, 1991 with the c axisin the fibre direction.

The plots show the angular distribution of orientations of this direction with a maxima at ± 30° in the dry timber in a polar form with the tilt angle shown as the radial distance from the centre and the rotation angle as the angle from the long axis. The dotted oval indicates 90° tilt. Figure 4 shows the same plot for the wetted timber with the same scale. The peaks corresponding to the angle of the crystallites have shifted through an angle of approximately 60°. This may indicate a change in the microfibrillar angle but may be also associated with changes of the distribution and arrangement of crystallites within the helical microfibrils.

Small angle neutron scattering experiments have been performed to elucidate these changes using the LOQ small angle spectrometer at the ISIS neutron scattering facility at the Rutherford - Appleton Laboratories. Preliminary experiments on dried timber have indicated that the scattering arises from dilute blocks of approximately 10 nm x 30 nm x 100 nm parallel to the timber grain and 25 nm x 25 nm x ~1 to 5 nm perpendicular to the grain. This is explainable if the crystallites within

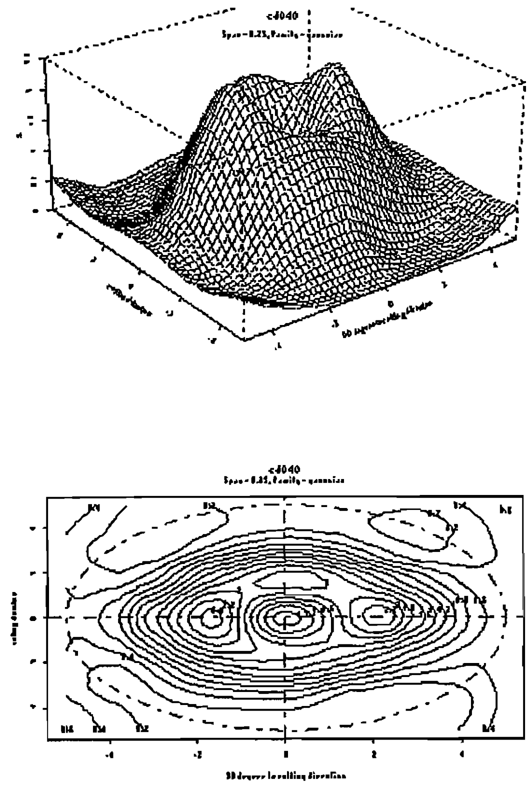


Figure 3 040 Pole Figure -Dry

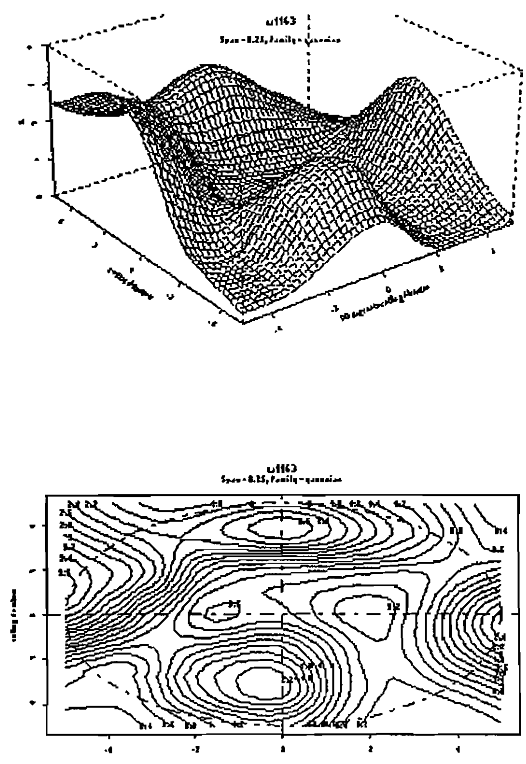


Figure 4 040 Pole Figure -Wet

the microfibrils are lathlike with a width of 25 nm, a thickness of 25-30 nm and >100 nm along the microfibril axis. Small angle scattering data parallel and perpendicular to the grain for dry Caribbean pine are given in Figures 5 and 6.

Figure 5: Parallel grain SANS pattern of dry Caribbean pine wood.

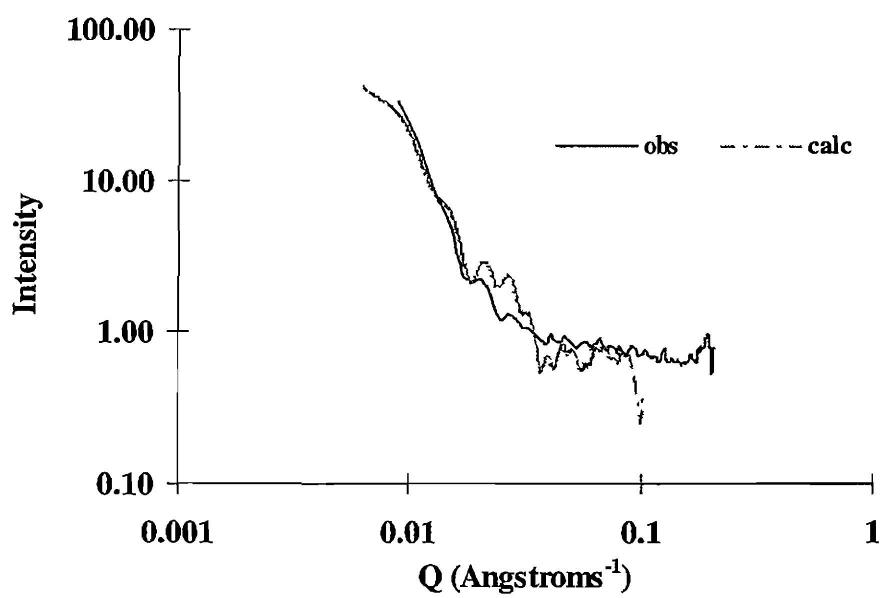
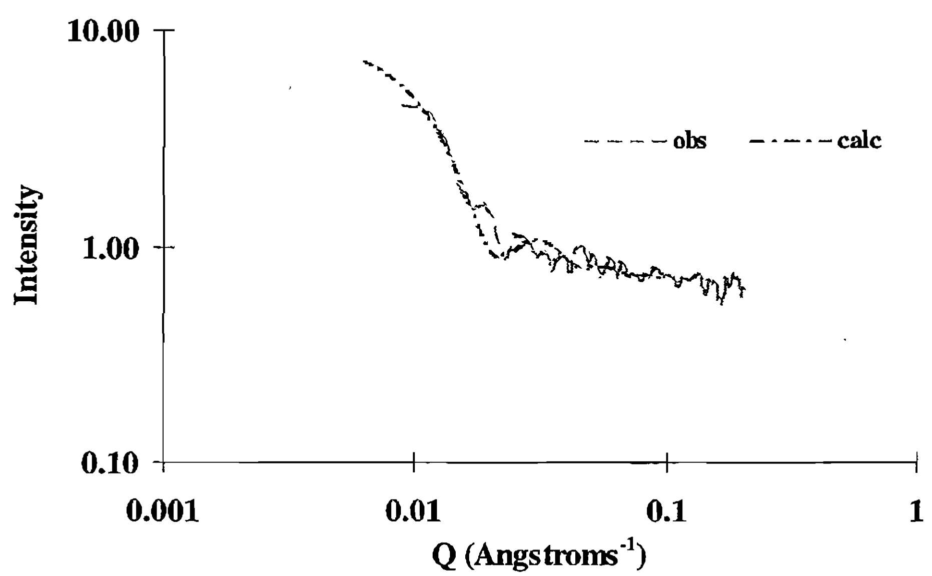


Figure 6: Perpendicular grain SANS pattern of dry Caribbean pine wood.



Further small angle scattering eperiments currently in progress on dry and rewetted caribbean pine will be used to further refine this model and used in conjunction with the XRD data to develop a model for the structure of the microfibrils and changes within that structure occurring during hydration. Optical diffraction studies are also currently in progress to extend this work to dimensions of the order of the cell widths.

Figure 7 Green early wood

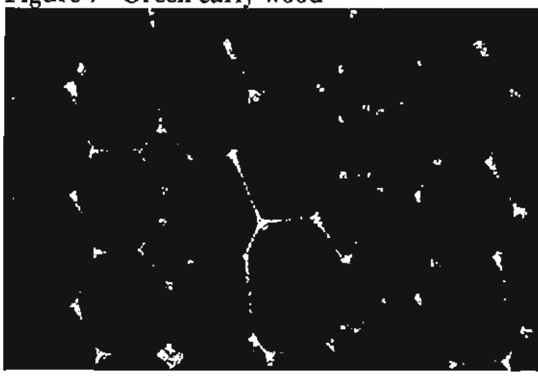


Figure 8 Green Late wood

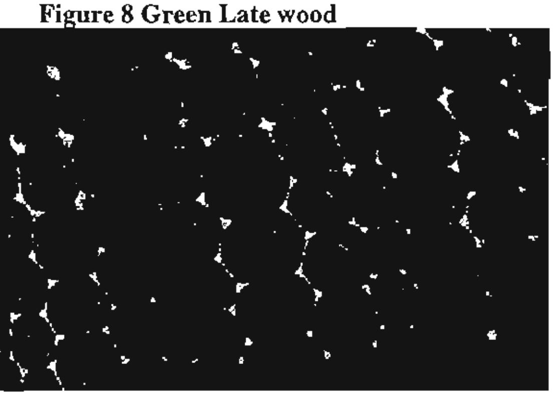


Figure 9 Dry early wood

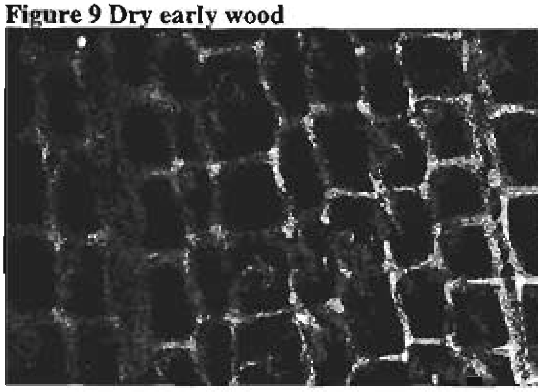


Figure 10 Wet early wood

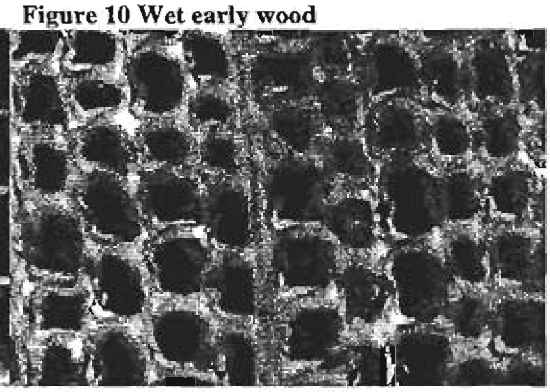


Figure 11 Dry late wood

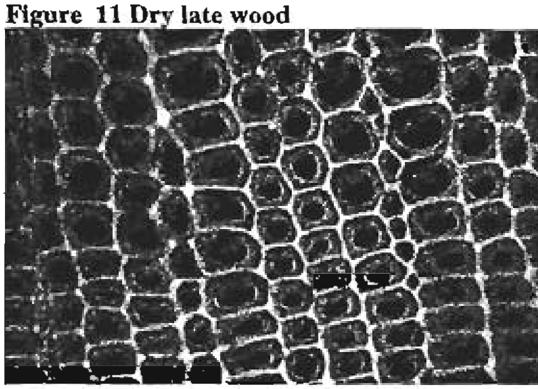
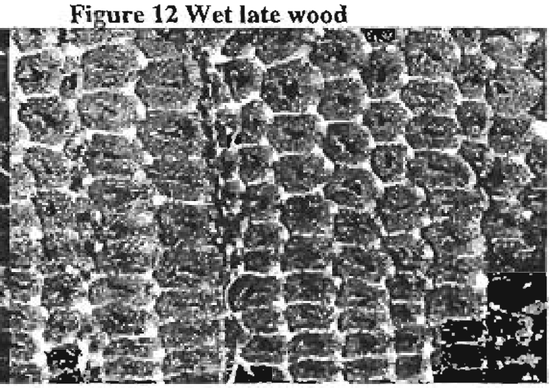


Figure 12 Wet late wood



Scanning confocal images from transverse sections of early and late wood in the green dried and rewetted state are shown in Figures 7 to 12. Changes in the structure from early to late wood, following drying and subsequent rewetting are illustrated. The major dimensions of the cells are largely unaltered by rewetting however significant changes occur in the layers of the cell wall. Series of these images from wet and dry early wood have been analysed by

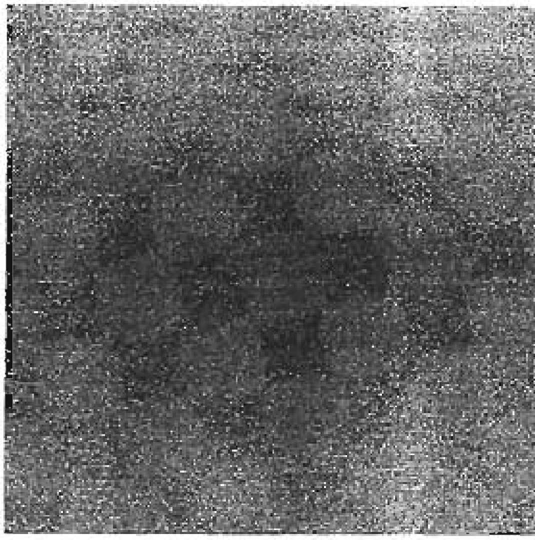


Figure 13 Combined FFT Power spectrum of dry early wood

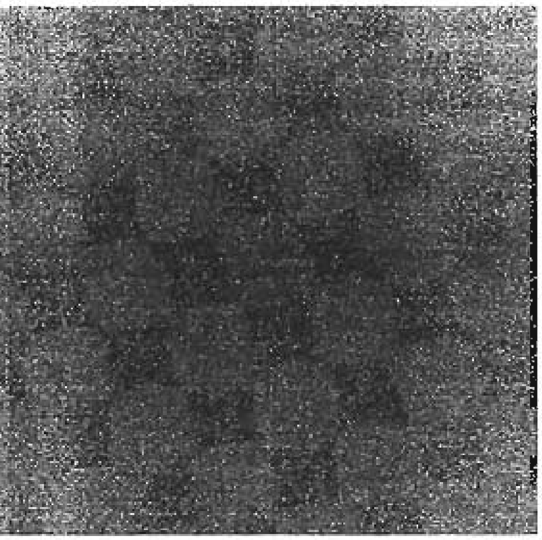


Figure 14 Combined FFT Power spectrum of rewetted early wood

Table 1 Summary of measured spacings in 04 and 05 Fourier transforms

Image	Spacing Invers	Error in position	Spacing Image (um	Error in spacing (ur	Angle (degrees)	Comment
4	24.52	1	18.29	0.75	4.7	dark
4	18.43	1	24.34	1.32	6.2	dark
4	17.46	1	25.69	1.47	33.5	dark
4	14.44	1	31.06	2.15	7.9	dark
4	13.09	1	34.26	2.62	141.3	dark
4	10.98	1	40.85	3.72	67.1	dark
4 *1	10.13	1	44.28	4.37	0.0	dark
4 *2	8.44	1	53.14	6.30	90.0	dark
4	4.67	1	96.04	20.57	135.0	dark
5	16.37	1	27.40	1.67	129.6	Bright
5	14.84	1	30.22	2.04	15.9	Dark
5	13.7	1	32.74	2.39	62.4	Dark
5	13	1	34.50	2.65	141.4	Bright
5	12.82	1	34.99	2.73	0.0	Dark
5 *2	11.69	1	38.37	3.28	121.6	Dark
5 *2	10.37	1	43.25	4.17	80.5	Dark
5 *1	7	1	64.07	9.15	0.0	
5	2.88	1	155.73	54.07	135.0	Dark
5	2	1	224.26	112.13	90.0	Dark

FFT methods with summation of the power spectra from 10 individual images within a growth ring to provide average information over that growth ring. FFT patterns from the dry and rewetted woods are illustrated in Figures 13 and 14.Table 1 contains measurements of the observed spacings in Figures 13 and 14 with corresponding values indicated in column 1 by a * followed by an index. Changes of the major horizontal direction from 44.28 to 64.07 μm and in vertical spacings between 53.14 and between 38.37 and 43.25 μm are observable. Each point is not however a single spot, but is a convolution of the basic structural change ie the thickening of the cell wall with the distribution of spacings within the image. The thickening of the cell wall is measured by the inverse of the size of the darkened diamond shape in the background of each of the FFTs of Figure 13 and 14. Further work is required to develop models of the disorder and distribution functions in the FFT spectra which may be used to extract these parameters from the images.

Experiments in the environmental SEM (ESEM) allow measurement of longitudinal changes in the cell dimensions on unprepared samples in contact with water condensed onto the surface of initially dry samples. The dimensional changes are measured between the centres of bordered pits in the cell walls. Initial measurements indicated both increases and decreases in the longitudinal dimensions of the cell of the order of +4.6% -3.2%. Modification of the experimental procedure to include cycling the lenses has reduced this spread to ~ 0.6 % µm. The previous experiments will be repeated to establish whether dimensional changes Have been affected by lens hysteresis.

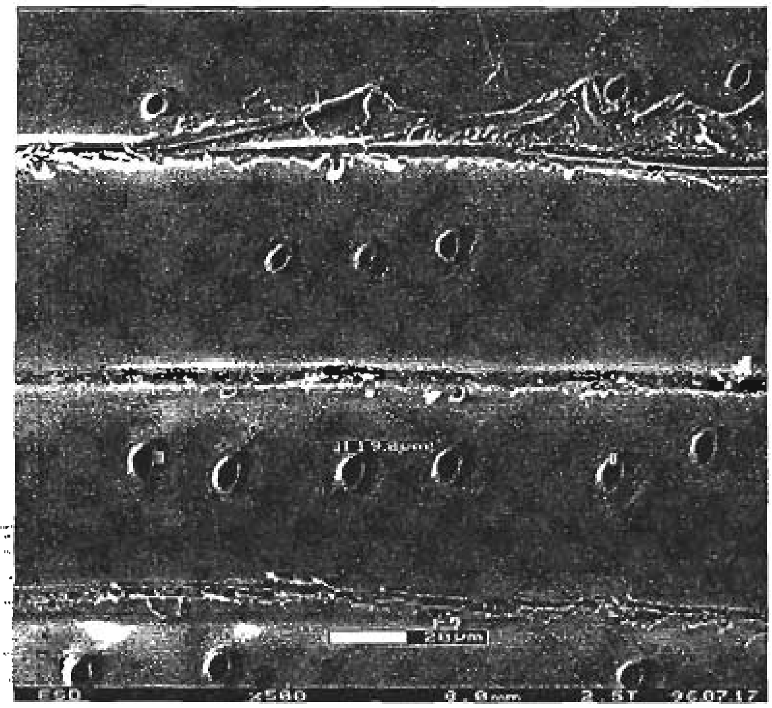


Figure 15 ESEM image of radial wall in early wood of Caribbean pine at dry stage. The same 12 pores (upper in the micrograph) were considered after wetting the specimen.

Optical diffraction measurements are currently under evaluation to complement the ESEM and SCM experiments. Full analysis of the FFT patterns is however necessary to measure the distribution of cell parameters and changes in those distributions with hydration.

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WHAT'S GOING UP IN SMOKE?

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ABSTRACT
Emission from wood drying plants is drawing increasingly more attention from general public and from bodies charged with the task of caring for our environment. Australian environmental legislations are conspicuously quiet on the issue of wood driers' emission, but it is more than likely that soon these will be brought in line with regulations of other countries. In this study, vapours emitting from the drying stacks are analysed and categorised and condensate characterised. The driers operational regime and parameters are examined and correlations between these and the character and the quantity of the emission postulated. The recovered condensate is a source of numerous organic compounds and some of these perhaps may be used on-site as additives to the particle board.

INTRODUCTION
Historically, when a wood panels manufacturing plant was built, it needed capital, a convenient location, source of raw materials and a market for the finished product. Today it still needs the same and in addition multiple environmental studies and permits. These permits are costly, time consuming and at times the longest lead-time item on a project. Most industrialised countries have legislation in place to limit and control negative impact that emission of pollutants may have on the environment. In the USA the allowable emission level from wood particle drying plants, such as MDF and particle board is $50mg/m^3$. Similar emission levels protect West European environment. In Australia, emission limits are subject to state legislation, NSW permits emission of particulate matter of $250mg/m^3$ and in Queensland the limit is $450mg/m^3$. There is no specification to limit the emission of condensable organic matter and non-condensable volatile compounds. It is the presence of these organic compounds that causes 'blue haze', a 'tell-tale' of air pollutants in the air. It is expected that Australia will adopt more stringent Clean Air control measures in line with the practices overseas. The 1990 Clean Air Act (CCA-'90) of the USA will provide a useful guideline. Previous Clean Air limits in New Zealand mirrored those of NSW, permitting emission of particulate matter up to $250mg/m^3$. Having no developed standards for measurements and monitoring of air quality, New Zealand is using measuring methods of Standards Australia. The recently legislated "Resource Management Act" (1991) has repealed the Clean Air Act (1972) and has placed the control of the legislation in the hands of the local council who will determine the acceptable limits. The industrial establishments when renewing their operating licence will have to present to the council their proposed limits and the nature of emission from their plants, and the new limits will be set. Practically the entire reconstituted wood panels industry in Australia is based on utilising softwood sawmilling wastes and plantation thinnings. Nearly 1,000,000 tons of panel products, consisting of particle board, medium density fibre board (MDF) and hardboard are produced annually. *Pinus radiata* and to a lesser extent *Pinus elliottii* are the main softwood species used in the wood panels manufacture. During the drying process a material loss of about 4% (OD basis) occurs. This loss represents a mixture of wood fines that are carried by the air stream past the cyclone collectors, a range of terpenoids that have either evaporated or steam distilled from the wood particles during the drying process, and products of partial pyrolysis that occur in small wood particles in contact with hot combustion gases issuing from the drier burners. The initial contact temperature may be as high as 500^oC. Effluents from the wood panels drying plants are released into the atmosphere, and are often responsible for the formation of 'blue haze'. Clean Air legislation will certainly limit the emission levels of the drying plants in the near future, necessitating the implementation of emission control measures. (D. Torner, 1992). Wet-dry electrostatic precipitators adjacent to the wood particle drying plants recover stack condensate of approximately 0.5% w/w (OD wood basis). An average particle board plant is processing 100,000 tons of product, and is expected to yield some 500 tons of terpenoid and pyrolysis by-products annually.

ORIGIN AND DIVERSITY OF TERPENOIDS
The biochemistry and the mobilisation of terpenoids in the woody species is poorly understood, but it is clear that the presence of these substances plays an important role in the defence and resistance of the plants and the environmental interaction of forest trees and their predators and parasites. (Shrimpton, 1978; Raffa and Berryman, 1982; Langenheim *et al.*, 1982). Conifers produce amounts and types of terpenoids that are without a parallel in the nature. The terpenoids are derived by the formal condensation of C5 isoprenoid units and they

range from the volatile monomer isoprene (C5) to the polymer rubber (MW~10,000,000). All plants use the same isoprenoid pathway in the process of synthesis of the essential substances, such as phtylol(C20), carotenoids(C40), dolichol phosphate(C100), steroids(C27), prenylated quinones and plant hormones(C15 C20) In the narrow range of species exist a diverse range of other terpenoids, classed as secondary metabolites, often stored in large quantities in the specialised compartment of a tree, offering ecological advantages to the species that accumulate them (Gibbs, 1974; Seigler, 1981a,b; Langenheim 1981). The terpenes are the most diverse group of wood extractives, but lend themselves to a simple classification by size.

The monoterpens (C10) consist of two main groups: the lipophylic, steam-volatile constituents of essential oils, and the hydrophylic, non-volatile iridoid glycosides. The sesquiterpens (C15) encompass a wider range of skeletal types and oxidation states than are usually found in the monoterpens (ie. furans, lactones) and are usually contained in the higher fractions of the essential oils. The diterpenes (C20) occur mainly as non-volatile resin acids, and lactones, but include some volatile hydrocarbons such as cembrene and rimuene. The triterpenes (C30) with the exception of their acyclic precursor, squalene, occur as C30 oxygenated polycyclic compounds. The triterpenes are non-volatile and often appear as glycosylated derivatives or saponins. The polyterpenes are long-chain acyclic alcohols (polyprenols) and polyisoprene polymers of a very high molecular weight (eg. rubber, gutta, chicle).Terpene accumulation has been observed in every plant organ in the variety of physical forms, including oils, resins, gums, latex and waxes (Dell and McComb, 1978a), and taxonomic distribution of terpene-accumulating plants has been the subject of extensive reviews (Hegnauer, 1962-1973; Gibbs, 1974; Seigler, 1981a,b). Bark extractives are similar to the extractives derived from wood.

CLASSICAL TERPENE EXTRACTIVES

Since ancient times naval stores industry has been the largest processor of terpene wood extractives, for the variety of end uses, including waterproofing of wooden ships. (Zinkel, 1981). Presently, conifer rosin (non-volatile terpenes) and turpentine (essential oil) are used to manufacture a wide range of industrial products, solvents, adhesives, polymers, emulsifiers, coatings and paper sizing (Weaver, 1982). The primary source of these oleoresins are *Pinus palustris* (longleaf pine), *Pinus elliotti* (slash pine) in the USA and *Pinus sylvestris* (Scots pine) in the former USSR and in Northern Europe (Koch, 1972). The main commercial process for collection of oleoresins is derived from chemical stimulation of new resin flow from pulpwood or from the living stumps. Flow of resin is stimulated by administering a paraquat-type herbicides in sublethal doses. Paraquat is effective in stimulating the resin production only in pines (Chemical Engineering News 16(3), 30, 1983). The monoterpenes, alpha- and beta-pinene are used for production of specialty chemicals (Hendrick *et al.*, 1965a,b; Zinkel, 1981, Weaver, 1981).

PARTIAL PYROLYSIS PRODUCTS

Drying process in a typical flake drier irrespective of the layout is designed to remove moisture from wet material in a short period of time, from 100-120% to final M.C. of 2-3%. Present technological processes to manufacture particle board product dictate harsh drying conditions in the driers. Most commercial adhesives, urea-formaldehyde, urea-melamine-formaldehyde and phenol-resorcinol-tannin- formaldehyde require high core curing temperatures. Additionally, water is produced as a product of condensation-polymerisation reaction of the adhesives, necessitating that the furnish moisture content be about 2%. The residence time for flake drying varies from 2 - 5 minutes, and the temperature gradient for the hot direct combustion gases is from about 500^{o}C at the point of flake-hot gas contact to 140-150^{o}C at the drier's exhaust. At the same time the wood flakes have been heated from ambient temperature to above 100^{o}C. It is probably that small wood particles undergo chemical changes would occur, while much larger particles are dried to 2% M.C., inside a drying system. Products of pyrolysis are found in the stack condensate, accounting for as much as 80% w/w of the total condensed mass. Relatively low temperatures in the flake dryers will be more conducive for production of pyrolytic oils rather than wood gasification, that normally takes place at elevated temperatures, above 700^{o}C.

DRYING CONDITIONS VARIABLES

No two particle board manufacturing plants are identical in design, equipment specification, raw material composition, fuels and subsequent forming and pressing processes. Removal of water from wood flakes is dependant upon contact of wet flakes and hot gases issuing from the furnace, flake size and thickness, wet flakes moisture content, drier inlet temperature, drier exhaust temperature, particle residence time and tumbling effect. Many plants have undergone throughput increase modifications. In most cases it meant increasing the drier inlet temperature, by stoking the furnace with more fuel.

a. Initial moisture content of wood flakes. Drier rating is expressed in the amount of water that the device is capable of removing from the material that is being dried, and the amount of water present in the wood flakes will determine main drying parameter. The variations extend from a 'dripping' green wood particles containing up to 160% of water, in wet cold winter periods, to planer mill shavings that have been kiln dried, containing 15% of water. Intermediate situations may include combination of raw material sources, sawdust, round wood, recycle particles and sawmill woodchips and seasonal weather variations. Since every plant manager is desirous of a steady material flow through the manufacturing process, the driers will be inherently operating under variable conditions to supply steady output of dry flakes, coping with feedstock differences.

b. Drier throughput. Most flake driers are designed for water evaporative capacity between 3,000 - 7,000 kg/hr. The rated drier performance can only be enhanced by increasing inlet temperature. Depending on type and design, these may range from 250°C to 500°C. Theoretically, wood particle temperature should not rise until all free and bound water is removed, but particle size non-uniformity can cause wood fines to dry rapidly and starting to pyrolyse in the ambient of hot oxidising gases. Obviously then, when drier performance is being increased, wood fines will dry more rapidly and partial pyrolysis is more likely to be a side reaction.

c. Drier design. The drying process efficiency is measured in energy requirement to remove 1kg of water, which is in the range of 750-1000 kcal, depending on the design of the drier. Particle board driers may be classified according to the working principle into;

1. Rotary drum driers, tube bundle driers
2. Multiple band driers
3. Contact driers
4. Turbo driers
5. Burned waste gas stream driers
6. Suspension type driers

High inlet temperature is the feature of older designs; rotary drum and tube bundle triple pass driers, compared to more recently developed driers; contact, jet and suspension types.

d. Types of fuel. At best particle board manufacturers are 'scavengers' of wood materials, lagging behind other wood based industries, sawmilling, plywood, pulp and paper and MDF, in choice of raw materials. Current furnace and drier designs reflect the industry's frugality. Manufacturing processes for particle board can only be profitable if the energy requirements are met by using own residues for drying and pressing. A generation ago, oil or gas were the chief energy source. With oil prices climbing most furnaces and driers were converted to run on wood waste. Conversion was not always an optimum realisation. Choice of fuel will be reflected in type and quantity of stack emission. Fuel with high ash content will result in high content of large particle emission >10m. Sander dust will also contribute to high particulate emission, complicated with the presence of adhesives, abrasives and waxes. When sander dust contributes more than 30% of the fuel needed to power the drier, particulate emission exceeds the NSW limit of 200mg/m^3. Some plants burn bark as the principal fuel. Bark fuel is characterised with high mineral content (2-3%), high tannin content (more than 20%) and low cellulose content. Unless furnace temperature is very high (above 1200 °C) and flue gases recirculated for afterburning, it is expected that stack emission will result in tarry resinous substances, derived chiefly from incomplete decomposition of lignin and tannin macromolecules.

e. Particle size. Prior to the arrival of MDF technology, and when sawmilling waste was not an issue of concern, primary source for particle board flakes was plantation thinnings roundwood. Flakes produced by flaking wood billets on drum flakers were uniform in shape and more importantly in thickness. Changes in the industry over the past two decades made it an imperative to consider lower grade and less uniform raw material, such as sawmilling waste slab and sawdust (which is also getting finer with use of finer gauge bandsaws), planer mill shavings, sugar mill residues and agricultural residues such as straw and flax. During drying small particles will dry faster owing to greater surface/mass ratio and reach 'bone-dry' condition before larger particles. It is conceivable that pyrolysis process will initialise on the surface of these fines.

PROJECTED USAGE OF TERPENE EXTRACTIVES

Inherent biological activities render terpenes of interest to the pharmaceutical industry. Terpenes are attractive material for synthesis of complex chemicals and biological reactants. Natural terpene extractives and their derivatives are also used as agricultural pesticides and even hormonal preparations (Silverstein, 1981; Norin, 1972). Monoterpens can also be used as combustible hydrocarbon fuels. About 40 litres of sesquiterpene mixture per tree per year can be obtained from *Copaifera multijuga* (Leguminosae). The future prospects of the terpene extractive industry will depend on finding new ways to stimulate production and on developing new markets. Significant contribution may be made by condensing the oleoresin fraction in the wood panels drying plants effluents. The development of new plants with desired traits of productivity and environmental adaptability should have considerable impact in providing the full range of terpenes necessary for commercial use (Calvin 1983; Farnum et al., 1983).

CHARACTERISATION AND COMPOSITION OF DRIER STACK CONDENSATE

Considering the coniferous nature of particle board raw material, it might be reasonable to assume that the composition of the condensate would reflect the composition of volatile terpenoids in wood. This is not exactly the case. While terpenoids were identified in the stack condensate, the bulk of the condensate originated from incomplete combustion in the furnace and the pyrolysis within the drying process itself. Hundreds, possibly thousands of various derivatives can be identified in the condensate, when adequate pre-separation is carried out prior to analytical processes. There are only two sources of condensate resins available in the region of Australia and New Zealand, and both are in New Zealand, from two electrostatic precipitators installed by Fletcher Wood Panels to their driers in Kumeu and Taupo plants. The two plants are very different in; drier design, furnace design, fuels, raw material, and the operating temperatures. To date, only samples from Taupo plant have been investigated;

a. condensate form. The condensate after leaving wet-electrostatic precipitator (E-Tube) can be in the form of sediment, (particles heavier than water), suspension (particles mixed with water in suspension), and floating resin (particles lighter than water) and foam. Floating resin is a black tarry substance, having specific gravity ~0.9 and pH ranging from 11-13, resulting from sodium hydroxide dousing of the E-Tube.

b. solubility. The condensate is partially soluble in most solvents, being almost completely soluble in strongly polar solvents; (MeOH and EtOH), some 75% soluble in petroleum ether, about 60% in chloroform and ether. Non-soluble residue, presumably charred wood particles and ash accounted for some 6% of the condensate.

c. steam/water distillation. A 50g sample was steam/water distilled. Only few droplets of oleoresin distillate were collected after 8hrs of distillation. The resin is largely non-volatile.

d. fractional distillation. At atmospheric pressure a 50g samples yielded only few droplets below 150^{o}C. Temperature rose rapidly to 240^{o}C. with little or no evaporation. Thermal degradation was observable above 200^{o}C. Vacuum distillation yielded marginally more distillate and thermal degradation was also observed.

e. moisture content. After drying a sample at 103^{o}C. overnight, a weight loss of 20.5% was recorded, presumably water and some volatile matter.

f. resin acids. Acids were precipitated according to the method for isolation of resin acids by addition of cyclohexylamine. A hard resinous precipitate accounted for 24.0% of the condensate.

g. free fatty acids. The FFA were extracted with 1N NaOH as an aqueous solution of Na-salts of FFA and precipitated with 2N HCl. Yield was 4.5%.

h. neutrals. The residue was evaporated to dryness, yielding 42%

Summary	
Non-soluble residue	**6.0%**
Moisture and volatiles	**20.5%**
Resin acids	**24.0%**
Free fatty acids	**4.5%**
Neutrals including phenols	**41.0%**
Losses	**4.0%**

POSSIBLE USES OF CONDENSATE PRODUCTS.

It was a concern for the environment and air quality that gave rise to the installation of pollution interceptors such as the E-Tube in the first place, and handling of condensate is considered an additional task. Most managers would be quite happy with just a neat disposal of this by-product, but in some cases, it just would not go away. Blockages, foaming and down-time are some of the problems experienced with this ungainly substance. There is a need for improvement of the technology that will make the handling easier, non-interfering with the production scheduling and possibly recyclable into the end product.

a. water repellent additive. Paraffin wax is routinely added to particle board and MDF to reduce the surface water absorption and swelling. Adding 0.8-1.5% of wax to the board improves water absorption properties quite significantly, but further addition does not seem to make much difference. Isolated resin acids are hard, waxy and have high boiling points appear to have good water repelling properties, and resin coated surface resists wetting by water. It is quite possible to use the resin acids fraction as a replacement for paraffin wax.

b. phenol resin compatible extender. Structural particle board used for flooring and other structural purposes is bonded by phenolic or tannin resin. In either case, the adhesive is dark brown coloured, resulting in dark coloured particle board. Significant portion of the condensate resin is composed of derivatives of lignin and tannins from wood, having -OH group. It is conceivable that extending of phenol or tannin adhesive with phenolic fraction of the condensate would not adversely affect the bonding, resulting in some saving.

EMISSION CONTROL

There are four main types of emission from particle board drying plants;

1. Large solid particles, >10m
2. Small solid particles, <10m
3. Small volatile organic particles, evaporated from the drying furnish and
4. products of partial pyrolysis in the furnaces and driers

SELECTION OF EMISSION CONTROL SYSTEMS

Criteria for selection of emission control systems will depend on what regulation is to be met and the degree of control.

1. What regulation is to be met?
2. What classes of particles need to be controlled to meet the regulation?
3. Capital and operational costs of each option.
4. Space requirement
5. Energy requirements
6. Safety aspects; fire, explosion, chemical pollution.

COMMERCIAL EMISSION CONTROL SYSTEMS;

Generally, effectiveness of dust particles separation from the gas stream is dependent on; particle size, aggregate state (solids or liquids), specific gravity of particles (denser particles are easier to remove), electrostatic properties and solubility in gases or liquids. It is known that the drying conditions vary from one plant to another and it would be difficult to recommend a single separation system that would be equally effective in every situation.

1. Wet scrubbers In conjunction with water recirculation system, secondary and multiple cyclones, wet scrubbers are quite effective in removing solid particles larger than 1.0m. It is in sub-micron condensable particle range that these devices lack effectiveness. Coupled however, with electrostatic separators as preliminary collectors, these devices perform well cooling gases and separating larger particles.

2. Fabric filters and bio-filters. Fabric filters are normally used to filter dust particles from the gas stream. The system would unsuitable for removal of tars and resins.

3. Sonic agglomeration devices. These devices use ultrasonic waves to align and precipitate particles out of the gas stream. Relatively high power requirement is a general characteristics of the system and handling of tarry substances is not well defined.

4. Centrifugal collectors. A number of collectors in which the centrifugal field is provided by a rotating member are commercially available. Often, the exhaust fan and dust collector are combined as a single unit. The effectiveness of these units is comparable to cyclone type separators. Again, formation of tar deposits would affect adversely the performance of the separators.

5. Venturi scrubbers. These devices are very popular in number of applications and the basic designs vary in regard to method of achieving the venture effect, wet or dry approach and the entrainment separator. Tarry build-up would also inhibit the optimal performance, as tar removal from the separator would prove troublesome. Some designs also demand high energy input. Efficiency of removing particles is best for particles above 1.0m in size.

6. Electrostatic separators. These devices are capable of removing small particles 0.1m to 1.0m from the gas stream. Developed primarily for the needs of mining industry as a method for beneficiation of minerals from sands, the electrostatic separators are used in food industry and in waste management. Geoenergy of USA has developed a electrostatic precipitator, the E-Tube and some 50 units have been installed to control emission from wood drying plants, two at Fletcher particle board in New Zealand. The precipitators are effective in most situations, with the exception of emission containing tars.

IN CONCLUSION

The direction of this research is aimed at the following aspects of wood panels processing activities;

1. Clearer understanding of what is actually happening inside wood drying plants, prerequisite conditions for genesis of pyrolytic products relative to the operational parameters, such as choice of input raw materials, driers design and operational regime, choice of fuels for the heat generation and how these factors influence production of stack emission, qualitatively and quantitatively. This aim will be achieved through observing and monitoring existing plants in operation aided by a simulation model of drying wood particles based on varying conditions of drying.

2. Characterisation of emission condensate by analytical methods, such as column chromatography, standard methods of preparative organic chemistry, determination physical properties, mass spectroscopy, IR spectroscopy, HPLC etc.

3. Survey of emission control system in use and investigation of what may be optimum design in order to control emission effectively. Handling of condensate by chemical and engineering means may be improved with better understanding of its composition and behaviour.

4. Investigate feasibility of utilising the condensate other than burning, preferably in wood panels manufacture, as water repellent additive and adhesive extender.

SIMULATION OF WOODFLAKE DRYING AND STATISTICAL ANALYSIS OF DRYING PARAMETERS

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Abstract
The drying and thermal degradation of wood flakes is investigated together with the range of products formed at temperatures ranging from 170 - 300°C. The dimensions of wood particles taken from wood flake driers varies from fines through to flakes measuring 30x6x0.6mm. The final moisture content of the furnish material normally ranges from 2-5%. This results in a much harsher drying process for smaller size particles than the larger and thicker flakes. Inlet temperatures vary with the type and design of drier, throughput rate, ambient temperature, and moisture content of the wood flake furnish. The inlet temperature of some commercial driers may reach 500-550°C [2]. This is substantially higher than the thresholds leading to the thermal degradation of wood. Woodmass losses, often refereed to as 'drying loss' is believed to arise from the decomposition of the finer wood particles.

Key words: woodflake, drying, thermodegradation, emission, partial pyrolysis, simulation, mathematical modelling

1 Introduction

The pyrolysis of wood occurs by the action of heat in the absence of oxidising agents or other catalysts. The wood does not combust, but thermally degrades into solid, liquid and gasesous phases. The degradation products may be formed in varying proportions, and with varying properties that appear to be dependent on the processing conditions and feedstock [1]. Organic materials containing cellulose decompose when subjected to heating, by two alternative pathways:

1. Thermodegradation of cellulosic material at temperatures below 300°C. This involves de-polymerisation by bond scission; elimination of water; formation of free radicals carbonyl, carboxyl, and hydroperoxide groups; evolution of CO and CO_2 and finally the production of a highly reactive carbonaceous char [4].

2. The second pathway, which occurs when the temperature of cellulosic material exceeds 300°C, is characterised by the cleavage of molecules by transglycosylation, fission, and disproportionation reactions generating a mixture of tarry anhydro-sugars and lower molecular weight volatile derivatives [5].

Oxidation of the reactive char gives smouldering or glowing combustion, and oxidation. The combustible volatiles give flaming combustion. Smouldering combustion can be regulated by the use of catalysts and inhibitors. The corresponding rate of oxidation range from oxidation of char to CO (DH = 22.9 kcal/mol) and CO_2 (DH = -88.5kcal/mol) [1]. Historically, the major product of pyrolysis has been charcoal. However the pyrolysis of wood for the generation of chemicals continues to be of importance, although it has tended to be overshadowed by the petrochemical industry. The objectives of the experiments described below are to:

1. determine the effect of particle size on the rate of thermal decomposition
2. identify which processing parameters responsible for decomposition
3. construct a mathematical model of the pyrolysis process

2 Materials and Method

2.1 Raw material preparation

Wood chips were obtained from CSR Wood Panels in Tumut. Pallman knife mills were used to reduce chips to flakes. The sample was a composite, taken before drying and the subsequent screen classifying process, which separates core and face material. The moisture content of the sample was determined using the oven dry weight method prior to sealing in a plastic bag to prevent drying out. The flakes were stored at 4°C to minimise biological degradation.

2.2 Experiment 1

One hundred grams of wood flakes were charged into a tared 300ml glass cylinder fitted with glass wool swabs at both ends to prevent wood fines from entering the vapour stream. A glass cylinder containing wet wood flakes was placed inside a heating device consisting of a glass tube with windings of electrical resistance wire element. A thermometer was also inserted between the charge cylinder and the tube. The heating tube was insulated with a thick layer (30mm) of mineral wool to prevent heat losses. Nitrogen gas was introduced to the charge cylinder via a conical flask half filled with water to monitor nitrogen flow through the system. A thermocouple probe was inserted into the wood flake charge and connected to a 'variac' control and the heating element. A water cooled condenser was connected to the outlet of the charge cylinder to condense vapours of water, wood resin and condensable products of pyrolysis.

The temperature control to the interior of the glass cylinder was set to the maximum of 190°C. Nitrogen flow was not metered, but the flow of nitrogen bubbles indicated flow through the system. After 4 hrs of drying at 190°C, heating was stopped. The flow of nitrogen was maintained for another 30 minutes to cool the charge. Flakes that appeared light brown in colour were transferred into a 1000 ml separating funnel and washed 4 times in 100 ml of 96% ethanol. The wood flakes were redried and reweighed. The ethanol extract was evaporated to dryness in a rotary vacuum evaporator and weighed. The recovered condensable fraction was extracted with 50 ml of chloroform, ether and petroleum ether. The solvent extracts were evaporated to dryness for yield determination and ^{1}H and ^{13}C NMR analysis. Dry ethanol extracts of wood flakes were also analysed using the same methods.

2.3 Experiment 2

Wet flakes were separated into four particle sizes using a vibrating screen. The mesh openings were 1.0, 3.0 and 6.0mm. Four sets of drying simulations were conducted:

- four tests (one for each particle size) in each temperature range from 170 - 290°C, at 20°C intervals in a stream of air,

- composite flake material (prior to size separation) in a stream of nitrogen temperature range 170-330°C, at 20°C intervals,

- composite flake material (prior to size separation) in a stream of air-temperature range 170-290°C at 20°C intervals,

- four tests (one for each particle size) in a stream of air for each 10°C temperature increment ranging from 190 - 300°C.

The phases of wood flake drying and pyrolysis are summarised in figure 2.

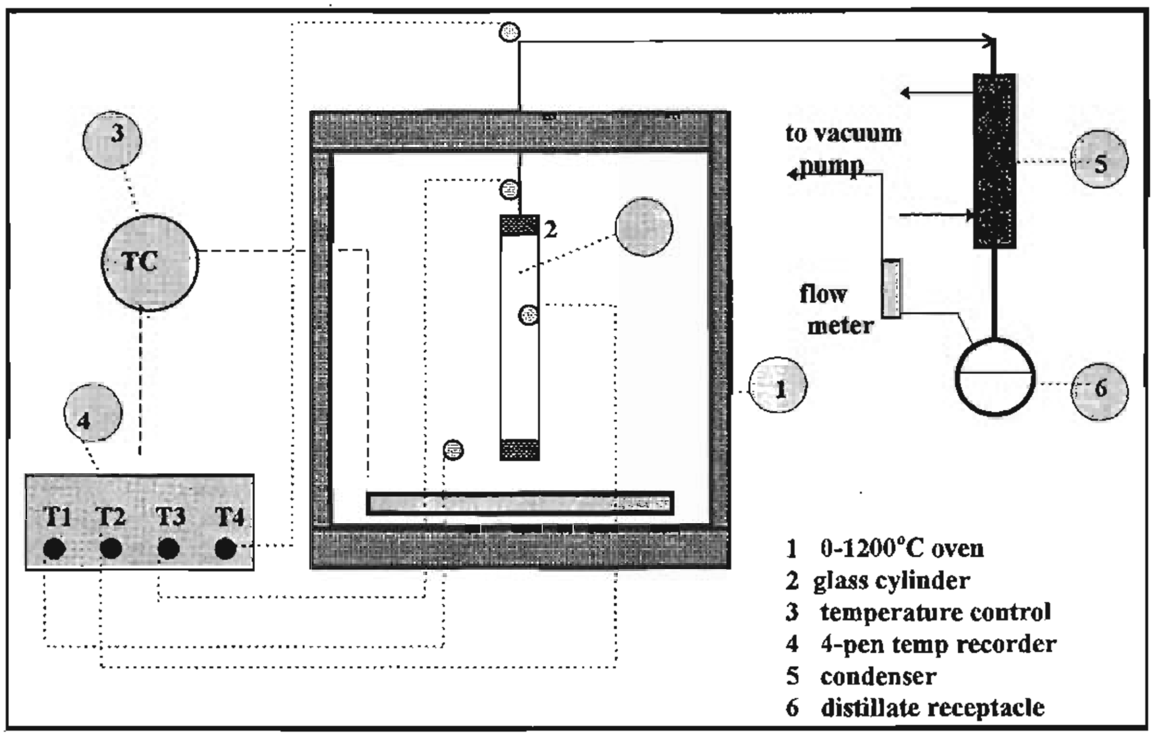

Fig 1 Wood flake drying apparatus used in Experiment 2

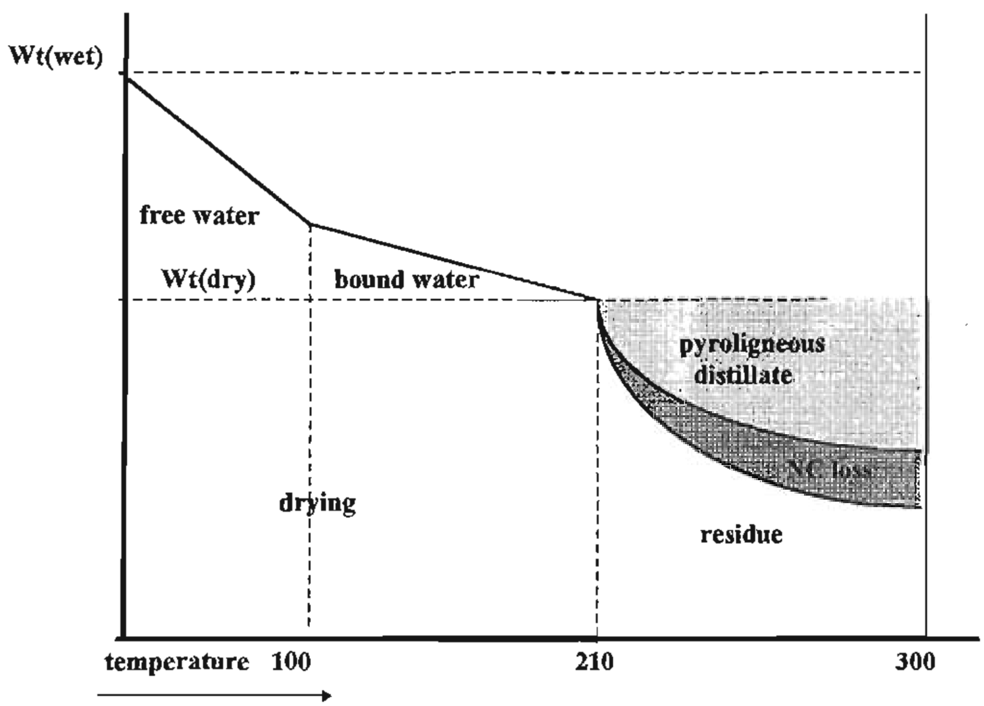

Fig. 2 Schematic diagram of wood drying and thermodegradation process as a function of temperature

The first *input* group - character of flakes:

Size	particle size of flakes
Wt_{wet}	wet weight of flakes
Wt_{dry}	dry weight of flakes
MC%	moisture content of flakes
H_2O	weight of water in flakes
Bulk	weight(wet) /volume of flakes

The second *input* group - character of heating parameters:

Temp	temperature after 2 hours heating
Time	time of heating is constant
ΔTemp	fluctuation of temperature in flakes
ΔTime	displacement between temperature phases
°C/m	calculated by temperature and wet flake weight
°C/m/g	calculated by temperature, wet flake weight and bulk
Vel	velocity of airstream

The first *output* group-the parameters of drying:

Residue	weight of dry flakes
Residue loss	loss of weight of flakes during drying
Residue loss%	percent loss of weight of flakes during drying

The parameters of water distillation:

Distill	weight of water after condensation
Distill gain	condensed pyrolysis liquid
Distill gain%	percentage condensed pyrolysis liquid

The parameters of emission:

NC loss	weight of non-condensable emission
NC loss%	percentage non-condensable emission

Fig 4 Parameter grouping by function

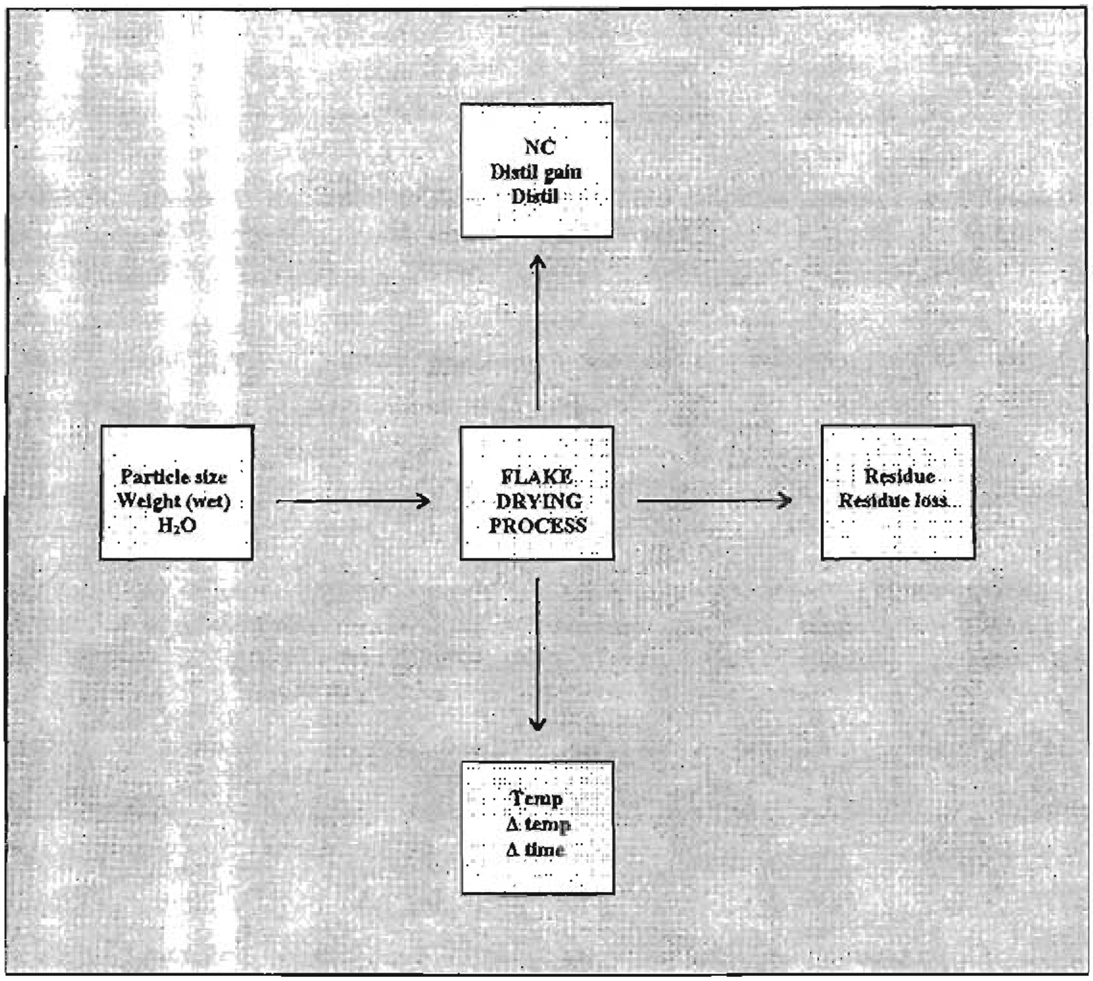

Fig. 5 Schematic diagram of drying process and parameters

Solution of the integral representation is given by Γ - function and hence:

$$\text{Residual} = -\int_{1/To}^{1/T} \exp(-Qp/(Rp*T))*T\uparrow 2*d(1/T) = Qp/Rp[G(-1,1/T)-G(-1,1/To)]$$

Thus the function Residual = f(Temperature) can be introduced by the Γ– function.

4.1 Correlation analysis of experimental data

Correlation analysis was undertaken to define the level of stochastic dependence and independence between the parameters of the experiments as illustrated in Fig 3. The computer program calculated the pair correlation between each of two parameters and can be considered to provide the level of correlation within and between each data group. The level of correlations in each data group from fig. 4 are illustrated below:

Table 1 The pair correlation between size, Wt(wet) and H_2O

Parameters	Size	Wet	H_2O
Size	1	0.07	0.07
Wt(wet)		1	0.99
H_2O			1

This illustrates strong functional dependence between the parameters "Wt(wet) and H_2O" (pair coefficient correlation r = 0.99.). This was illustrated in equation 3. The parameter "Size" illustrates no correlation with other parameters in the group.(r = 0.07)

Table 2 The pair correlation between Temp, ΔTemp, and ΔTime

Parameter	Temp	ΔTemp	ΔTime
Temp	1	0.55	-0.88
ΔTemp		1	-0.74
ΔTime			1

This illustrates a different stochastic dependence between the energy parameters. The highest negative level of correlation is found between "Temp" and "ΔTime". This is explained by the time differential between temperatures which decreases when the ambient heating temperature has increased.

Table 3 Pair correlation between "Wt(residual)" and "Wt(residual loss)"

Parameter	Wt(residual)	Wt(residual loss)
Wt(residual)	1	0.92
Wt(residual loss)		1

The parameters have a strong interrelationship (r = 0.92).

Table 4. Pair correlation between "Distill and "Distill gain"

Parameter	Distill	Distill gain
Distill	1	0.87
Distill gain		1

The high correlation (r = 0.87) is explained by the greater volume of water distillation giving rise to greater water emission during the flake drying process.

Table 5. Level of interaction between "NC" and other parameters

Parameter	Size	H_2O	Temp	ΔTemp	ΔTime	Distill	Distill gain	Wt(residual)	Wt(residual loss)
NC	0.01	-0.24	-0.92	-0.47	0.7	-0.81	0.91	0.9	0.95

Table 5 cont'd

Parameter	Wtwet	Wtdry	Bulk	°C/m	°C/m/g
NC	-0.24	-0.22	-0.34	-0.92	-0.907

Table 5 illustrates a high level of correlation between "NC" and ΔTemp, Distill, Distill gain, Wt(residual), Wt(residual loss), °C/m and °C/m/g. The parameter "Distill loss" comprises one of two components of emission. These include "Distill loss" and "Wt(residual loss)", (equation7). "Wt(residual)" was selected as one of the main criteria of the wood flake drying process.

Table 6 Correlation between Wt(residual) and other variables

Para-meter	Size	Temp	Wt (wet)	Wt (dry)	H_2O	Distill	Distill gain	Wt(res-loss)	ΔTemp
Wt(resi-dual)	-0.02	-0.82	0.16	0.18	0.17	-0.62	-0.92	0.91	-0.80

Table 6 cont'd

Parameters:	ΔTime	°C/m	°C/m/g	Bulk	NC
Wresidual	0.68	-0.84	-0.92	0.04	0.90

"Wt(residual)" has a strong independent relationship with "Temp", "Distill gain", "Wt(residual loss)", and "NC". "Wt(residual)" also has strong dependent relationships between ""°C/m" and ""°C/m/g". The parameters "Size", "Wt(wet)", "H_2O", "Wt(dry)" and "Bulk" have poor correlations with "Wt(residual)".

4.2 Regression analysis of the experimental data

The principles applying to heat transfer in wood flakes are complicated. In theory wood particle temperature should not rise until all free and bound water is removed. However, wood fines dry rapidly and start pyrolysing in the hot oxidising gases. Regression analysis is used to model the interactions between input and output parameters. The step-wise analysis outlined below defines:

- the physical and chemical steps occurring during drying and wood pyrolysis together with a statistical model of each step.
- the best statistical model for describing the interaction between variables.
- The significant parameters included in the model.
- The removal of unimportant parameters.
- The level of independence of parameters in the statistical model.

The following assumptions were made in applying regression analysis:

1. a linear relationship exists between parameters in the statistical model

2. random parameters have a normal distribution

3. the minimum number of experimental observations is equal to n+1, where 'n' is number of samples in the statistical model

4. the wood flake drying process is considered to be a "random process" because parameter values continually change during the time of experimental observations.

The best regression equation describing the inter-relationship between parameters was selected using an analysis of standard errors and their distribution, residual square and F-criteria for confidence levels of 0.05. These are given together with the coefficients of the regression equation

The total standard error, the mean square, residual square and F-criteria indicate that the regression is significant. However, the most significant parameters determined by t-test are given in equation 10.

$$\mathbf{Wt(residual) = -0.0029Temp - 0.9481Distill + 1.7742H_2O + 1.0471NC + 0.3907} \quad (10)$$

Table 7 Regression analysis of drying and wood pyrolysis

Parameters:	Coefficients	Standard Error	t-test	Mean square
x0-intercept	0.0340	1.5698	0.02167	α=0.05
x1-Temp	0.0046	1.0024	1.9221	51.02
x2-Distill	0.7722	0.0498	15.5150	Residual 0.01
x3-Distill gain	-2.3351	0.8997	-2.5984	F=4412.31
x4- Distill gain %	0.4974	0.2384	2.0869	Significance:
x5-Wt(residual loss)	0.3066	0.8460	0.3623	7.16E-20
x6-Wt(residual loss %	0.2170	0.1899	1.1490	Observations:
x7-ΔTemp	-0.0023	0.0078	-0.2992	24
x8-ΔTime	0.0064	0.0041	1.5488	
x9-°C/m	0.7982	0.5981	1.2176	
x10-°C/m/g	-34.691	29.068	-1.1934	
x11-NC	-0.1996	0.1361	-1.4663	

This equation had the maximum F-value and minimum residual standard error. Independent parameters such as Size, Bulk, Wt(wet), Wt(dry), ΔTemp, and ΔTime had relatively little impact on the drying process. The variables "Residual loss" and "Distill gain" are incorporated into the parameter NC. Comparison of equations 9 and 10 indicates that similar variables influence Wt(residual) except for the parameter "Temp" which was absent in equation 9.

Wtresidual = - 0.0029Temp - 0.9481Distill + 1.7742H2O + 1.0471NC + 0.3907 **(10)**

Temp r= -0.82	**ΔTemp r= -0.88**	**Temp r= 0.88**	**Wwet r= 0.99**	**Temp r= -0.92**
Distill r= -0.62	**ΔTime r= 0.55**	**Wwet r= 0.65**	**Distil r= 0.65**	**Distil r= -0.82**
NC r= 0.90			**Bulk r=0.96**	**ΔTime r= 0.78**
ΔTem r= 0.80				
ΔTime r= 0.68				

The kinetic function of wood flake pyrolysis in the <u>solid phase</u> is described by equation 11 and is illustrated in figure 7.

$$\mathbf{Residual = Wt(dry)*exp\ (-0.118*(To-T)} \quad (11)$$

Summary	
Non-soluble residue	**6.0%**
Moisture and volatiles	**20.5%**
Resin acids	**24.0%**
Free fatty acids	**4.5%**
Neutrals including phenols	**41.0%**
Losses	**4.0%**

POSSIBLE USES OF CONDENSATE PRODUCTS.

It was a concern for the environment and air quality that gave rise to the installation of pollution interceptors such as the E-Tube in the first place, and handling of condensate is considered an additional task. Most managers would be quite happy with just a neat disposal of this by-product, but in some cases, it just would not go away. Blockages, foaming and down-time are some of the problems experienced with this ungainly substance. There is a need for improvement of the technology that will make the handling easier, non-interfering with the production scheduling and possibly recyclable into the end product.

a. water repellent additive. Paraffin wax is routinely added to particle board and MDF to reduce the surface water absorption and swelling. Adding 0.8-1.5% of wax to the board improves water absorption properties quite significantly, but further addition does not seem to make much difference. Isolated resin acids are hard, waxy and have high boiling points appear to have good water repelling properties, and resin coated surface resists wetting by water. It is quite possible to use the resin acids fraction as a replacement for paraffin wax.

b. phenol resin compatible extender. Structural particle board used for flooring and other structural purposes is bonded by phenolic or tannin resin. In either case, the adhesive is dark brown coloured, resulting in dark coloured particle board. Significant portion of the condensate resin is composed of derivatives of lignin and tannins from wood, having -OH group. It is conceivable that extending of phenol or tannin adhesive with phenolic fraction of the condensate would not adversely affect the bonding, resulting in some saving.

EMISSION CONTROL

There are four main types of emission from particle board drying plants;

1. Large solid particles, >10m
2. Small solid particles, <10m
3. Small volatile organic particles, evaporated from the drying furnish and
4. products of partial pyrolysis in the furnaces and driers

SELECTION OF EMISSION CONTROL SYSTEMS

Criteria for selection of emission control systems will depend on what regulation is to be met and the degree of control.

1. What regulation is to be met?
2. What classes of particles need to be controlled to meet the regulation?
3. Capital and operational costs of each option.
4. Space requirement
5. Energy requirements
6. Safety aspects; fire, explosion, chemical pollution.

COMMERCIAL EMISSION CONTROL SYSTEMS;

Generally, effectiveness of dust particles separation from the gas stream is dependent on; particle size, aggregate state (solids or liquids), specific gravity of particles (denser particles are easier to remove), electrostatic properties and solubility in gases or liquids. It is known that the drying conditions vary from one plant to another and it would be difficult to recommend a single separation system that would be equally effective in every situation.

1. Wet scrubbers In conjunction with water recirculation system, secondary and multiple cyclones, wet scrubbers are quite effective in removing solid particles larger than 1.0m. It is in sub-micron condensable particle range that these devices lack effectiveness. Coupled however, with electrostatic separators as preliminary collectors, these devices perform well cooling gases and separating larger particles.

2. Fabric filters and bio-filters. Fabric filters are normally used to filter dust particles from the gas stream. The system would unsuitable for removal of tars and resins.

3. Sonic agglomeration devices. These devices use ultrasonic waves to align and precipitate particles out of the gas stream. Relatively high power requirement is a general characteristics of the system and handling of tarry substances is not well defined.

4. Centrifugal collectors. A number of collectors in which the centrifugal field is provided by a rotating member are commercially available. Often, the exhaust fan and dust collector are combined as a single unit. The effectiveness of these units is comparable to cyclone type separators. Again, formation of tar deposits would affect adversely the performance of the separators.

5. Venturi scrubbers. These devices are very popular in number of applications and the basic designs vary in regard to method of achieving the venture effect, wet or dry approach and the entrainment separator. Tarry build-up would also inhibit the optimal performance, as tar removal from the separator would prove troublesome. Some designs also demand high energy input. Efficiency of removing particles is best for particles above 1.0m in size.

6. Electrostatic separators. These devices are capable of removing small particles 0.1m to 1.0m from the gas stream. Developed primarily for the needs of mining industry as a method for beneficiation of minerals from sands, the electrostatic separators are used in food industry and in waste management. Geoenergy of USA has developed a electrostatic precipitator, the E-Tube and some 50 units have been installed to control emission from wood drying plants, two at Fletcher particle board in New Zealand. The precipitators are effective in most situations, with the exception of emission containing tars.

IN CONCLUSION

The direction of this research is aimed at the following aspects of wood panels processing activities;

1. Clearer understanding of what is actually happening inside wood drying plants, prerequisite conditions for genesis of pyrolytic products relative to the operational parameters, such as choice of input raw materials, drier's design and operational regime, choice of fuels for the heat generation and how these factors influence production of stack emission, qualitatively and quantitatively. This aim will be achieved through observing and monitoring existing plants in operation aided by a simulation model of drying wood particles based on varying conditions of drying.

2. Characterisation of emission condensate by analytical methods, such as column chromatography, standard methods of preparative organic chemistry, determination physical properties, mass spectroscopy, IR spectroscopy, HPLC etc.

3. Survey of emission control system in use and investigation of what may be optimum design in order to control emission effectively. Handling of condensate by chemical and engineering means may be improved with better understanding of its composition and behaviour.

4. Investigate feasibility of utilising the condensate other than burning, preferably in wood panels manufacture, as water repellent additive and adhesive extender.

SIMULATION OF WOODFLAKE DRYING AND STATISTICAL ANALYSIS OF DRYING PARAMETERS

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Abstract
The drying and thermal degradation of wood flakes is investigated together with the range of products formed at temperatures ranging from 170 - 300°C. The dimensions of wood particles taken from wood flake driers varies from fines through to flakes measuring 30x6x0.6mm. The final moisture content of the furnish material normally ranges from 2-5%. This results in a much harsher drying process for smaller size particles than the larger and thicker flakes. Inlet temperatures vary with the type and design of drier, throughput rate, ambient temperature, and moisture content of the wood flake furnish. The inlet temperature of some commercial driers may reach 500-550°C [2]. This is substantially higher than the thresholds leading to the thermal degradation of wood. Woodmass losses, often refereed to as 'drying loss' is believed to arise from the decomposition of the finer wood particles.

Key words: woodflake, drying, thermodegradation, emission, partial pyrolysis, simulation, mathematical modelling

1 Introduction

The pyrolysis of wood occurs by the action of heat in the absence of oxidising agents or other catalysts. The wood does not combust, but thermally degrades into solid, liquid and gasesous phases. The degradation products may be formed in varying proportions, and with varying properties that appear to be dependent on the processing conditions and feedstock [1]. Organic materials containing cellulose decompose when subjected to heating, by two alternative pathways:

1. Thermodegradation of cellulosic material at temperatures below 300°C. This involves de-polymerisation by bond scission; elimination of water; formation of free radicals carbonyl, carboxyl, and hydroperoxide groups; evolution of CO and CO_2 and finally the production of a highly reactive carbonaceous char [4].

2. The second pathway, which occurs when the temperature of cellulosic material exceeds 300°C, is characterised by the cleavage of molecules by transglycosylation, fission, and disproportionation reactions generating a mixture of tarry anhydro-sugars and lower molecular weight volatile derivatives [5].

Oxidation of the reactive char gives smouldering or glowing combustion, and oxidation. The combustible volatiles give flaming combustion. Smouldering combustion can be regulated by the use of catalysts and inhibitors. The corresponding rate of oxidation range from oxidation of char to CO (DH = 22.9 kcal/mol) and CO_2 (DH = -88.5kcal/mol) [1]. Historically, the major product of pyrolysis has been charcoal. However the pyrolysis of wood for the generation of chemicals continues to be of importance, although it has tended to be overshadowed by the petrochemical industry. The objectives of the experiments described below are to:

1. determine the effect of particle size on the rate of thermal decomposition
2. identify which processing parameters responsible for decomposition
3. construct a mathematical model of the pyrolysis process

2 Materials and Method

2.1 Raw material preparation

Wood chips were obtained from CSR Wood Panels in Tumut. Pallman knife mills were used to reduce chips to flakes. The sample was a composite, taken before drying and the subsequent screen classifying process, which separates core and face material. The moisture content of the sample was determined using the oven dry weight method prior to sealing in a plastic bag to prevent drying out. The flakes were stored at 4°C to minimise biological degradation.

2.2 Experiment 1

One hundred grams of wood flakes were charged into a tared 300ml glass cylinder fitted with glass wool swabs at both ends to prevent wood fines from entering the vapour stream. A glass cylinder containing wet wood flakes was placed inside a heating device consisting of a glass tube with windings of electrical resistance wire element. A thermometer was also inserted between the charge cylinder and the tube. The heating tube was insulated with a thick layer (30mm) of mineral wool to prevent heat losses. Nitrogen gas was introduced to the charge cylinder via a conical flask half filled with water to monitor nitrogen flow through the system. A thermocouple probe was inserted into the wood flake charge and connected to a 'variac' control and the heating element. A water cooled condenser was connected to the outlet of the charge cylinder to condense vapours of water, wood resin and condensable products of pyrolysis.

The temperature control to the interior of the glass cylinder was set to the maximum of 190°C. Nitrogen flow was not metered, but the flow of nitrogen bubbles indicated flow through the system. After 4 hrs of drying at 190°C, heating was stopped. The flow of nitrogen was maintained for another 30 minutes to cool the charge. Flakes that appeared light brown in colour were transferred into a 1000 ml separating funnel and washed 4 times in 100 ml of 96% ethanol. The wood flakes were redried and reweighed. The ethanol extract was evaporated to dryness in a rotary vacuum evaporator and weighed. The recovered condensable fraction was extracted with 50 ml of chloroform, ether and petroleum ether. The solvent extracts were evaporated to dryness for yield determination and ^{1}H and ^{13}C NMR analysis. Dry ethanol extracts of wood flakes were also analysed using the same methods.

2.3 Experiment 2

Wet flakes were separated into four particle sizes using a vibrating screen. The mesh openings were 1.0, 3.0 and 6.0mm. Four sets of drying simulations were conducted:

- four tests (one for each particle size) in each temperature range from 170 - 290°C, at 20°C intervals in a stream of air,
- composite flake material (prior to size separation) in a stream of nitrogen temperature range 170-330°C, at 20°C intervals,
- composite flake material (prior to size separation) in a stream of air-temperature range 170-290°C at 20°C intervals,
- four tests (one for each particle size) in a stream of air for each 10°C temperature increment ranging from 190 - 300°C.

The phases of wood flake drying and pyrolysis are summarised in figure 2.

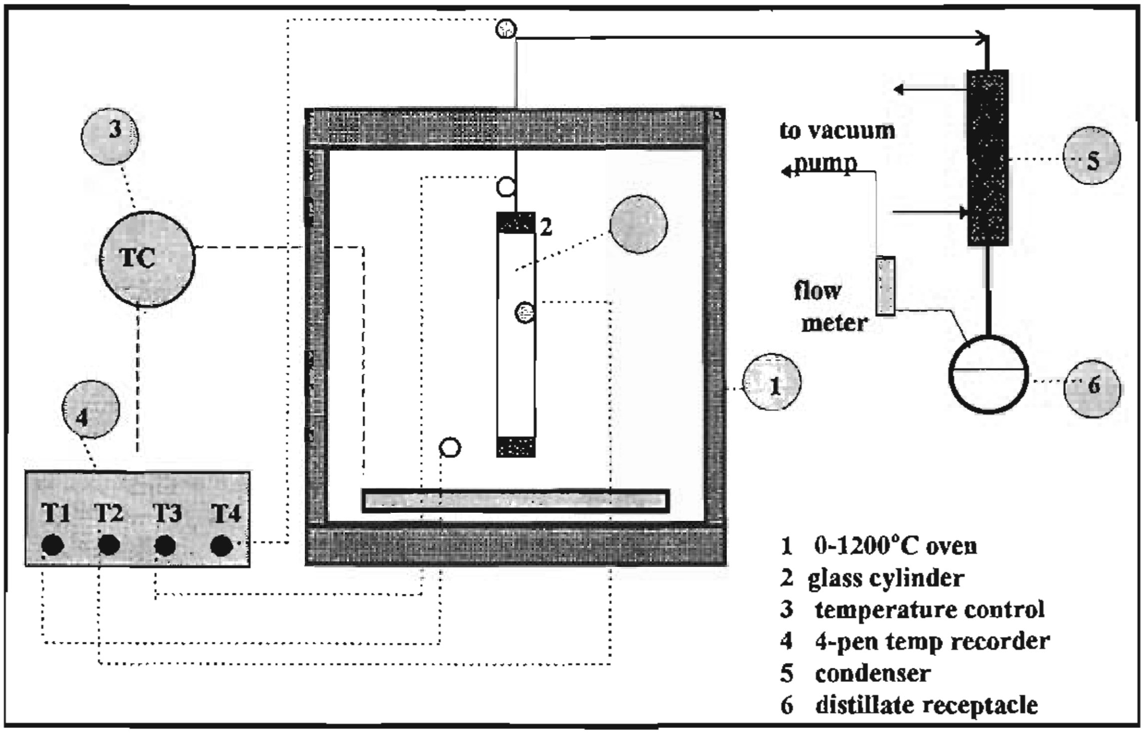

Fig 1 Wood flake drying apparatus used in Experiment 2

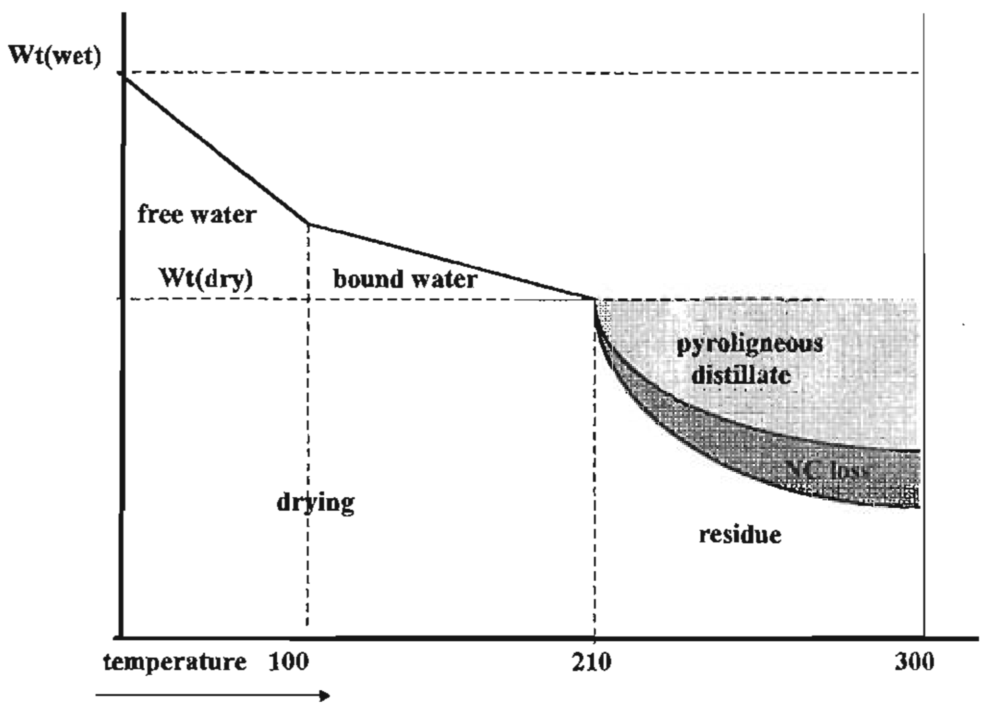

Fig. 2 Schematic diagram of wood drying and thermodegradation process as a function of temperature

3 Statistical analysis

The process is dynamic, involving heat and mass transfer from a moving front. the pyrolysis products also vary with temperature and time. To assist modelling of the process, all variables were identified in terms of 'input' and 'output' parameters [3]. A schematic layout of experimental data for flake drying is illustrated in fig 3. There are two input groups of parameters and three output groups. Multidimensional statistical analysis was used to define the level of independence between the parameters in the input and output groups. The physical independence of the parameters in the first input group - Wt(wet) - the wet weight of flakes, MC% - moisture content of the flakes; H_2O - weight of water in flakes; Wt(dry) - dry weight of flakes and Bulk - the weight of wet flakes per unit volume). Bulk (which is defined as weight of lose wet flakes per unit of volume, could be introduced by the dependence: Bulk=f*Wwet, where f is the coefficient of wood flake density. There are only two independent parameters (Wt(wet) & H_2O) so Wt(dry) = Wt(wet) - H_2O.

The second input group of energy parameters include (Temperature, Time, ΔTemperature, ΔTime, °C/minute, and °C/minute/gram). The parameter Time is constant and °C/m and °C/m/g are dependent parameters and are calculated by using other parameters. The parameters Temperature, ΔTemperature, ΔTime are independent. Velocity of airstream (0.5l/min) is constant during the experiments. The analysis of independence in output groups shows that the parameters (Residual, Residual loss, Distillate, Distillate loss, Non-condensables) are independent. Fig. 3 illustrates and defines the input and output parameters without identifying interdependency between variables.

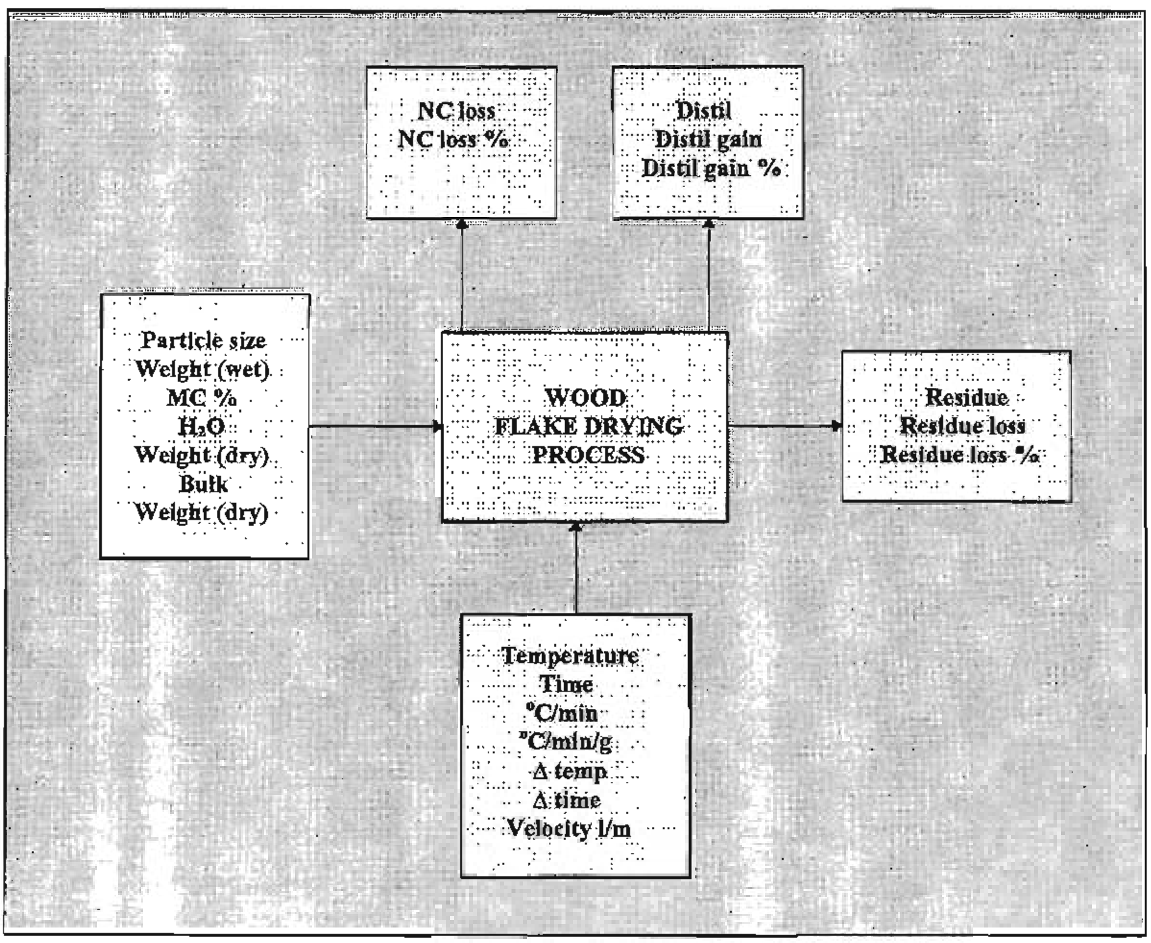

Figure 3 Schematic diagram of input and output variables

4 Results and Discussion

The mathematical interaction between the input and output groups of the parameters (which reflect the material balance of the flake drying process when the final heating temperature is constant) is illustrated in Fig 4 The equations used for defining these input and output parameters are outlined below;

$MC\% = 100\%*(Wt(wet) - Wt(dry) / Wt(wet)$ - (1)
or $MC\% = 100\%*(W(wet) - W(dry)/Wt(dry)$ - (2)
$Wt(wet) = MC\% / 100\% * H_2O$ - (3)
$Wt(dry)=MC\% / 100\% * H_2O$ - (4)
and consequently $Wt(wet) = Wt(dry) + H_2O$ - (5)
and $H_2O = Wt(wet) - Wt(dry)$ - (6)
The parameter "Wt(residual)" is described by the equations:
$Wt(residual) = Wt(dry) + Wt(residual\ loss)$ or $Wt(residual\ loss) = Wt(residual) - Wt(dry)$
and consequently;
$Wt(residual) = Wt(wet) - H_2O + Wt(residual\ loss)$ or $Wt(residual) = Wt(dry) + Wt(residual\ loss)$ - (7)
and so; $Distill = H_2O + Distill\ gain$ and $NC = Wt(residual\ loss) + Distill\ gain$
$Wt(residual = Wt(wet) - (Distill-Distill\ gain) + Wt(residual\ loss)$ - (8)
$Wt(residual) = Wt(wet) - Distill + NC$ or $Wt(residual) = MC\% / 100\% * H_2O - Distill + NC$ - (9)

Equation (9) reflects the flake drying mass balance between the weight of flakes, water and its emission during heating to the final constant temperatures. The purpose of the analysis to find stochastic dependencies between the material balance and the final heating temperatures.

Before building a statistical model of wood flake pyrolysis, the theoretical dependence of Residual = f (Temperature) is considered. The physical velocity of evaporation of free water is given by: $V = \exp(-Q/(R*T))$, where Q = the heating energy for evaporating 1 mol of free water - kcal/mol and R - cal/(1degree*mol). It is assumed that the velocity of pyrolysis has the same form, but parameters Q and R have different levels and hence $d(Residual/d(Temp.) = \exp(-Qp/(Rp*T))$ or $d(Residual) = \exp(-Qp/(Rp*T))*d(T)$, but $d(1/T) = -d(T)/T\uparrow 2$. When d(T) takes place the differential gives:

$$d(Residual) = -\exp(-Qp/(Rp*T))*T\uparrow 2*d(1/T)$$

The integral gives:

$$Residual = -\int_{1/To}^{1/T} \exp(-Qp/(Rp*T))*T\uparrow 2*d(1/T)$$

Where Qp = level of heating energy for evaporating 1 mol of bound water, Rp = coefficient cal/(1degree*mol), To = temperature at the beginning of pyrolysis and T = current temperature.

The first *input* group - character of flakes:

Size	particle size of flakes
Wt_{wet}	wet weight of flakes
Wt_{dry}	dry weight of flakes
MC%	moisture content of flakes
H_2O	weight of water in flakes
Bulk	weight(wet) /volume of flakes

The second *input* group - character of heating parameters:

Temp	temperature after 2 hours heating
Time	time of heating is constant
ΔTemp	fluctuation of temperature in flakes
ΔTime	displacement between temperature phases
°C/m	calculated by temperature and wet flake weight
°C/m/g	calculated by temperature, wet flake weight and bulk
Vel	velocity of airstream

The first *output* group-the parameters of drying:

Residue	weight of dry flakes
Residue loss-	loss of weight of flakes during drying
Residue loss%-	percent loss of weight of flakes during drying

The parameters of water distillation:

Distill	weight of water after condensation
Distill gain	condensed pyrolysis liquid
Distill gain%	percentage condensed pyrolysis liquid

The parameters of emission:

NC loss	weight of non-condensable emission
NC loss%	percentage non-condensable emission

Fig 4 Parameter grouping by function

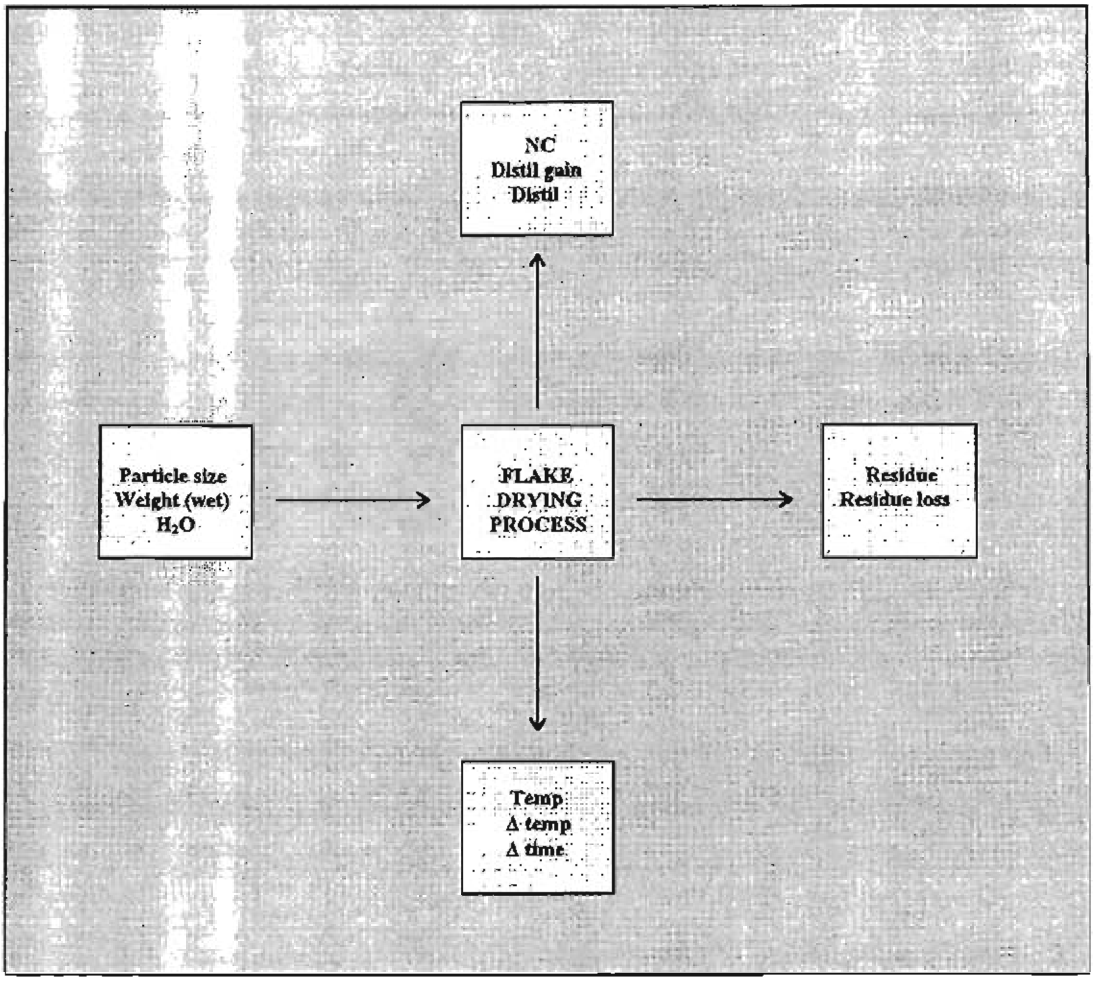

Fig. 5 Schematic diagram of drying process and parameters

Solution of the integral representation is given by Γ - function and hence:

$$\text{Residual} = -\int_{1/To}^{1/T} \exp(-Qp/(Rp*T))*T\uparrow 2*d(1/T) = Qp/Rp[G(-1,1/T)-G(-1,1/To)]$$

Thus the function Residual = f(Temperature) can be introduced by the Γ– function.

4.1 Correlation analysis of experimental data

Correlation analysis was undertaken to define the level of stochastic dependence and independence between the parameters of the experiments as illustrated in Fig 3. The computer program calculated the pair correlation between each of two parameters and can be considered to provide the level of correlation within and between each data group. The level of correlations in each data group from fig. 4 are illustrated below:

Table 1 The pair correlation between size, Wt(wet) and H_2O

Parameters	Size	Wet	H_2O
Size	1	0.07	0.07
Wt(wet)		1	0.99
H_2O			1

This illustrates strong functional dependence between the parameters "Wt(wet) and H_2O" (pair coefficient correlation $r = 0.99$.). This was illustrated in equation 3. The parameter "Size" illustrates no correlation with other parameters in the group.($r = 0.07$)

Table 2 The pair correlation between Temp, ΔTemp, and ΔTime

Parameter	Temp	ΔTemp	ΔTime
Temp	1	0.55	-0.88
ΔTemp		1	-0.74
ΔTime			1

This illustrates a different stochastic dependence between the energy parameters. The highest negative level of correlation is found between "Temp" and "ΔTime". This is explained by the time differential between temperatures which decreases when the ambient heating temperature has increased.

Table 3 Pair correlation between "Wt(residual)" and "Wt(residual loss)"

Parameter	Wt(residual)	Wt(residual loss)
Wt(residual)	1	0.92
Wt(residual loss)		1

The parameters have a strong interrelationship ($r = 0.92$).

Table 4. Pair correlation between "Distill and "Distill gain"

Parameter	Distill	Distill gain
Distill	1	0.87
Distill gain		1

The high correlation ($r = 0.87$) is explained by the greater volume of water distillation giving rise to greater water emission during the flake drying process.

Table 5. Level of interaction between "NC" and other parameters

Parameter	Size	H_2O	Temp	ΔTemp	ΔTime	Distill	Distill gain	Wt(residual)	Wt(residual loss)
NC	0.01	-0.24	-0.92	-0.47	0.7	-0.81	0.91	0.9	0.95

Table 5 cont'd

Parameter	Wtwet	Wtdry	Bulk	°C/m	°C/m/g
NC	-0.24	-0.22	-0.34	-0.92	-0.907

Table 5 illustrates a high level of correlation between "NC" and ΔTemp, Distill, Distill gain, Wt(residual), Wt(residual loss), °C/m and °C/m/g. The parameter "Distill loss" comprises one of two components of emission. These include "Distill loss" and "Wt(residual loss)", (equation7). "Wt(residual)" was selected as one of the main criteria of the wood flake drying process.

Table 6 Correlation between Wt(residual) and other variables

Para-meter	Size	Temp	Wt (wet)	Wt (dry)	H_2O	Distill	Distill gain	Wt(res-loss)	ΔTemp
Wt(resi-dual)	-0.02	-0.82	0.16	0.18	0.17	-0.62	-0.92	0.91	-0.80

Table 6 cont'd

Parameters:	ΔTime	°C/m	°C/m/g	Bulk	NC
Wresidual	0.68	-0.84	-0.92	0.04	0.90

"Wt(residual)" has a strong independent relationship with "Temp", "Distill gain", "Wt(residual loss)", and "NC". "Wt(residual)" also has strong dependent relationships between "°C/m" and "°C/m/g". The parameters "Size", "Wt(wet)", "H_2O", "Wt(dry)" and "Bulk" have poor correlations with "Wt(residual)".

4.2 Regression analysis of the experimental data

The principles applying to heat transfer in wood flakes are complicated. In theory wood particle temperature should not rise until all free and bound water is removed. However, wood fines dry rapidly and start pyrolysing in the hot oxidising gases. Regression analysis is used to model the interactions between input and output parameters. The step-wise analysis outlined below defines:

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- the best statistical model for describing the interaction between variables.
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The following assumptions were made in applying regression analysis:

1. a linear relationship exists between parameters in the statistical model

2. random parameters have a normal distribution

3. the minimum number of experimental observations is equal to n+1, where 'n' is number of samples in the statistical model

4. the wood flake drying process is considered to be a "random process" because parameter values continually change during the time of experimental observations.

The best regression equation describing the inter-relationship between parameters was selected using an analysis of standard errors and their distribution, residual square and F-criteria for confidence levels of 0.05. These are given together with the coefficients of the regression equation

The total standard error, the mean square, residual square and F-criteria indicate that the regression is significant. However, the most significant parameters determined by t-test are given in equation 10.

$$Wt(residual) = -0.0029Temp - 0.9481Distill + 1.7742H_2O + 1.0471NC + 0.3907 \quad (10)$$

Table 7 Regression analysis of drying and wood pyrolysis

Parameters:	Coefficients	Standard Error	t-test	Mean square
x0-intercept	0.0340	1.5698	0.02167	α=0.05
x1-Temp	0.0046	1.0024	1.9221	51.02
x2-Distill	0.7722	0.0498	15.5150	Residual 0.01
x3-Distill gain	-2.3351	0.8997	-2.5984	F=4412.31
x4- Distill gain %	0.4974	0.2384	2.0869	Significance:
x5-Wt(residual loss)	0.3066	0.8460	0.3623	7.16E-20
x6-Wt(residual loss %	0.2170	0.1899	1.1490	Observations:
x7-ΔTemp	-0.0023	0.0078	-0.2992	24
x8-ΔTime	0.0064	0.0041	1.5488	
x9-°C/m	0.7982	0.5981	1.2176	
x10-°C/m/g	-34.691	29.068	-1.1934	
x11-NC	-0.1996	0.1361	-1.4663	

This equation had the maximum F-value and minimum residual standard error. Independent parameters such as Size, Bulk, Wt(wet), Wt(dry), ΔTemp, and ΔTime had relatively little impact on the drying process. The variables "Residual loss" and "Distill gain" are incorporated into the parameter NC. Comparison of equations 9 and 10 indicates that similar variables influence Wt(residual) except for the parameter "Temp" which was absent in equation 9.

Wtresidual =	- 0.0029Temp	- 0.9481Distill	+ 1.7742H2O	+ 1.0471NC	+ 0.3907
					(10)
Temp r= -0.82	**ΔTemp r= -0.88**	**Temp r= 0.88**	**Wwet r= 0.99**	**Temp r= -0.92**	
Distill r= -0.62	**ΔTime r= 0.55**	**Wwet r= 0.65**	**Distil r= 0.65**	**Distil r= -0.82**	
NC r= 0.90			**Bulk r=0.96**	**ΔTime r= 0.78**	
ΔTem r= 0.80					
ΔTime r= 0.68					

The kinetic function of wood flake pyrolysis in the solid phase is described by equation 11 and is illustrated in figure 7.

$$Residual = Wt(dry)*exp\ (-0.118*(To-T) \quad (11)$$

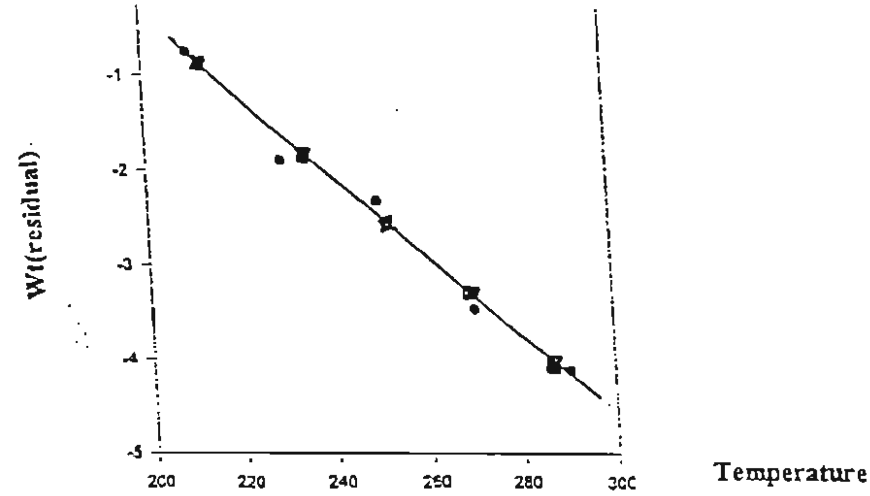

Fig. 7. Degradation of wood flakes as function of temperature.
■ - experimental points,
● - theoretical points

The kinetic function of wood pyrolysis in the liquid phase is described by equation (12) and is illustrated in figure 8.

Residual = Wt(dry) - Distill gain + NC loss, (12)

Where:

Wt(dry) = initial weight of wood flakes, Distill gain = 3.23 *exp(-0.11812*(To-T)/10)

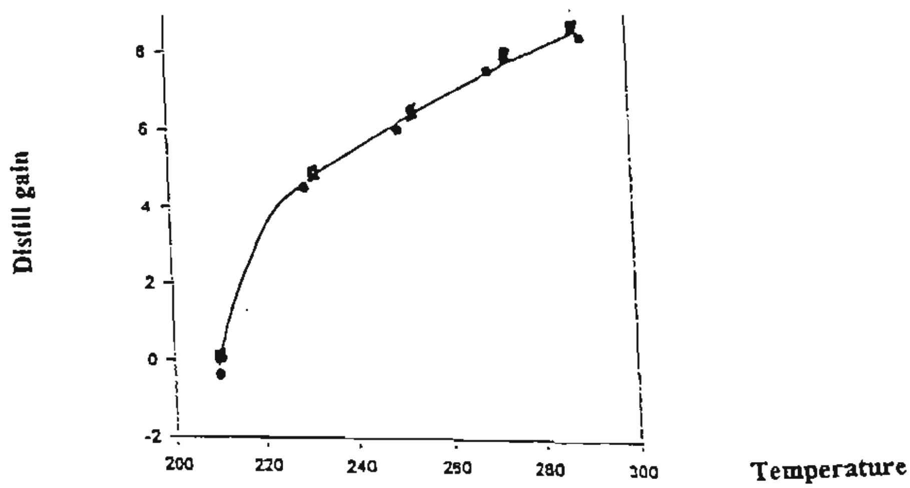

Fig. 8. Distill gain of wood flakes as function of temperature.
■ - experimental points,
● - theoretical points

NC loss is described by equation (13) and illustrated in figure 9.

$$\text{NC loss} = -1.54 * \text{exr}(0.11813*(\text{To} - \text{T}) \quad (13)$$

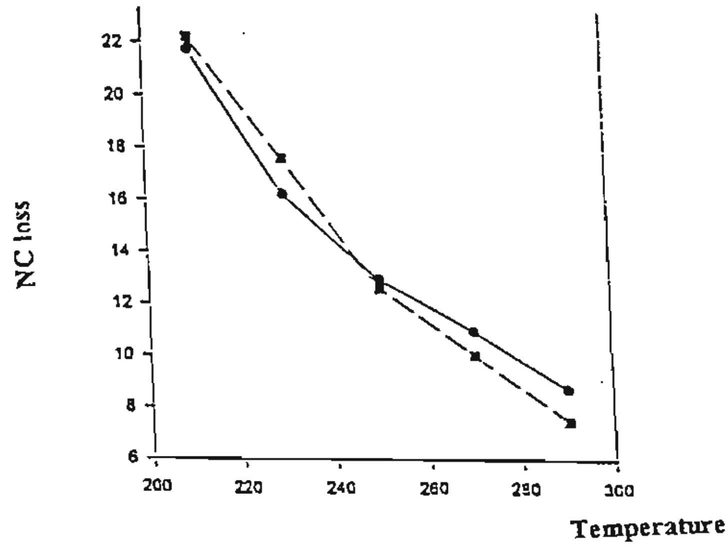

Fig. 9. NC loss as a function of temperature.
■ - experimental points,
● - theoretical points

The Residual (liquid phase) is given by equation (14)

$$\text{Residual} = \text{Wt(dry)} - 4.22*\exp(-0.118*(\text{To-T}) \quad (14)$$

The parameters influencing wood flake degradation during heating are the same for each equation. Figure 6 illustrates that "Distill gain" and Wt(residual) loss increase sharply at temperatures above 210°C. Below this temperature there is evaporation of free water, bound water and condensation from the wood flakes. Pyrolysis of the wood flakes then occurs yielding different fractions into the condensable liquid product. The pyrolysis oil is a mixture of different organic compounds which were included in the equation of the material balance as the total parameter "Distill gain". Similarly "Wt(residual loss)" is a mixture of different pyrolysis compounds. Equation (10) provides the statistical model for the pyrolysis of wood flakes.

5 Results and Conclusions

This paper introduces a statistical method and model of complex physical and chemical processes arising during the drying and pyrolysis of wood flakes. The purposes of this statistical approach are to:

- identify the interactions between input and output data, during monitoring the processes and to:

- build equations of the material balance when the heating temperature is constant or variable.

The statistical analysis shows that variables such as the size of the flakes, the temperature differential inside and outside flakes, (Δtemp) and Δtime) have weak influences on the level of emission (NC) and residual weight (Wt(residual). The weight of free and bound water in the wood flakes (H_2O) together with temperature is the most influential parameters in determining the rate of drying and pyrolysis of wood flakes. However, it should be noted that these conclusions are valid for temperatures ranging from 170 - 290°C.

The most practical results obtained from the statistical analysis are the dependence between the main parts of emission ("Distill gain" and "Wt(residual loss") and final heating temperature and also the dependence between the parameter "Wt(residual)" and the water weight, final temperature, weight of distillate and weight of emission. Further research is needed including:

- low temperature pyrolysis of wood flakes in the absence of air
- low temperature pyrolysis for low moisture content of wood flakes in airstream
- low temperature pyrolysis of high moisture content flakes in an airstream

This research is aimed at characterising wood panel processing by building a hierarchical system of statistical and mathematical models for describing what is happening inside wood flake drying plant. This provides further opportunities for *in situ* monitoring of wood flake drying and pyrolysis at the commercial plant and developing software and hardware for direct monitoring and optimisation; reporting and control of commercial drying plant.

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RELATIONSHIPS BETWEEN INTERNAL CHECKING AND BOARD DIMENSIONS, GRAIN ORIENTATION AND PREHEATING IN MOUNTAIN ASH

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Abstract

Assessment of the effect of board dimension, grain orientation and preheating on internal checking in end-sealed board sections of mountain ash has shown that: (1) by comparision with 5X10 cm material, internal checking in 5X5 cm and 2.5X10 cm control samples was reduced by 91.2 and 97.0% respectively; (2) while preheating 5X10 cm material at 50 and 70°C produced a decrease in internal checking for tangential grain, there was little change for intermediate grain and a substantial increase for radial grain; (3) preheating 5X10 cm material at 90°C, however, reduced internal checking by 77.8, 56.9 and 55.6% for tangential, intermediate and radial grain respectively; (4) irrespective of grain orientation, preheating 5X10 cm samples at 90°C produced an increase in shrinkage in width and a decrease in shrinkage in thickness; and (5) notwithstanding relationships between internal checking and shrinkage, the pre-eminent association with reduced checking was an increase in the drying rate.

Introduction

Internal checking during drying poses severe problems for the successful utilization of ash-eucalypt timber. The phenomenon is associated with collapse-shrinkage, but is much more damaging since external collapse can be substantially recovered by steam reconditioning. Once formed, internal checking is permanent (Chafe *et al.* 1992).

Efforts to reduce internal checking through the modification of drying regimes have been only partly successful. This is because the phenomenon is likely, in the main, a consequence of collapse and, although the contributory cause, drying stress, can be reduced by milder drying schedules, it is virtually impossible to design drying conditions that will not cause some collapse in collapse-prone species (Chafe *et al.* 1992).

Recent attempts to reduce internal checking have focused on preheating green material (Chafe 1994, 1995a). In the past, preheating has been used to produce increased drying rates and shorter drying times (Campbell 1961; Ellwood and Erickson 1962; Haslett and Kininmonth 1986), results generally attributed to increased permeability (MacKay 1971; Chen 1975) through a heat-induced change in the conformation of wood extractives (Kininmonth 1971; Alexiou *et al.* 1990). At the same time, preheating increases shrinkage and collapse (Kauman 1961; Haslett and Kininmonth 1986; Chafe 1990, 1992, 1994), putatively through a reduction in cell wall strength (Campbell 1961; Rosen and Laurie 1983). The reduction in internal checking, therefore, may be linked to increased external shrinkage, possibly through a reduction of internal collapse stresses (Chafe 1995a, 1995b).

To help further refine the effects of preheating, different sized material of differing grain orientations were selected for study. These results show the variability of internal checking and clarify relationships with shrinkage and permeability.

MATERIALS AND METHODS

Thirteen 3.5-metre-long boards, *ca.* 5 by 10 cm in cross-section, and each from a different tree of 55-year-old *Eucalyptus regnans* F. Muell regrowth from East Gippsland, Victoria, were used in the study. Boards were sorted by grain orientation as evident in cross-section into categories of tangential (flat sawn; five boards), radial (quarter sawn; four boards) or intermediate (four boards). Thirty sections, nine centimetres in length along the grain, were cut from each board. The first, and every third section thereafter, were retained as 5 by 10 cm cross sections; the second, and every third section to follow, were cut into 5 by 5 cm cross sections; and the third and every third to follow were cut into 2.5 by 10 cm cross-sections. The first six and the last six sections were retained as controls, while the remaining 18 sections were reserved for preheating. All samples were weighed, measured and end-sealed with a silicon compound and metal foil.

Six sections each of pretreatment samples were placed in water at 20°C and heated to 50, 70 or 90°C in a water bath (gradual preheating); three sections of each of these were then removed from the water bath while the remaining three were further heated at that temperature for the time taken for the samples to reach that temperature from 20°C (gradual preheating extended). Subsequently, preheated and extended preheated samples for any one temperature were grouped together for analysis since internal checking was found to be little different between the two.

All samples were dried in a conditioning chamber for 26 days at 30°C and 90% relative humidity (RH) and subsequently at 30°C and 67% RH to a nominal EMC of 12%. They were reweighed, measured and then oven dried (103°C) to 0% moisture content (M). Following further reweighing and measuring, samples were cross-cut at the centre and 2 mm thick sections were removed. These were measured for cross sectional area using image analysis software developed by J. Ilic, CSIRO. Area of internal checking and number of checks were recorded.

After drying and assessments by image analysis, the following shrinkages were calculated:

$S_{wo} = 100(W_g - W_o)/W_g$;
$S_{to} = 100(T_g - T_o)/T_g$;
$S_{vi} = 100A_i/A_g$;

S_{wo} = shrinkage in width to 0% M,
W_g = green width,
W_o = width at 0% M,
S_{to} = shrinkage in thickness to 0% M,
T_g = green thickness,
T_o = thickness at 0% M,
S_{vi} = internal checking represented as a percentage of green area,
A_g = green area = W_gT_g, and
A_i = area of internal checking.

For diagrammatic representation, dried boards were also measured at the edges and the centre of the cross-section for width and thickness, and along both diagonals.

Basic density (S_g) and moisture contents were calculated for all samples and, in addition, rate of moisture loss to 12% EMC, expressed as evapourable moisture available, was calculated by

$E_{12r} = [100-\{100(M_{12}-EMC)/(M_i-EMC)\}]/T_{12}$ where

E_{12r} = rate of loss of evapourable moisture available,

M_{12} = actual moisture content at 12% EMC,

EMC = 12%,

M_i = initial moisture content, and

T_{12} = drying time to 12% EMC.

Area per volume green (A_{pvg}) was calculated as the surface area of the sample, excluding the (end-coated) board ends, divided by the sample volume.

Regression analyses were carried out on a microcomputer using Statistix Version 4.1 software and all graphs were composed using Sigmaplot V3-10.

RESULTS AND DISCUSSION

Size and shape of sample

The effect of size and shape of board cross-sections on internal checking is shown in Figures 1 and 2. While 5X10 cm samples showed severe checking, matched 5X5 and 2.5X10 cm samples were largely free of this defect, although collapse was often evident (Fig. 2). Figure 3a graphically demonstrates this comparative checking (S_{vi}) for all control samples and Figure 3b shows, by comparision with 5X10 cm samples, the percentage reduction (δS_{vip}) in smaller samples: 94.2 and 99.3% for tangential grain for 5X5 and 2.5X10 cm respectively, 93.9 and 97.4% for intermediate grain, and 84.7 and 93.6 for radial grain. In all cases, checking was lowest in 2.5X10 cm samples.

Figures 3c-3e show how the reduction in checking (δS_{vi}) for the smaller samples was related to corresponding changes in shrinkage and rate of moisture loss. Thus: the greater the increase in shrinkage in width (S_{wo}), the greater the reduction in checking (Fig. 3c); the greater the reduction in shrinkage in thickness (S_{to}), the greater the reduction in checking (Fig. 3d); and the greater the increase in the rate of moisture loss (E_{12r}), the greater the reduction in checking (Fig. 3e). These relationships indicate that there are measurable factors by which the change in checking between larger and smaller samples can be determined.

Preheating

The effect of preheating on subsequent changes in internal checking is shown for 5X10 cm samples in Figures 4 to 6. Figure 4 shows a control intermediate grain sample (left), and matched samples preheated at 70°C (centre) and 90°C (right); checking was less than the control at 70°C and essentially absent at 90°C. Figure 5 shows a control tangential grain sample (left), and matched samples preheated at 90°C (centre) and 90°C extended heating (right). Both 90°C samples showed reduced checking but, overall, there was little difference between the effects of gradual preheating and gradual preheating extended.

Figure 6a demonstrates that while S_{vi} declined more or less continuously from 20 to 90°C for tangential grain, for radial grain it increased for 50 and 70°C before declining at 90°C. S_{vi} for intermediate grain was intermediate between the two (Fig. 6a). At 90°C, percentage reduction for S_{vi} was 77.8, 56.9 and 55.6% for tangential, intermediate and radial grain respectively, and 64.5% overall (Fig. 6b). Such changes in internal checking after preheating are generally in agreement with previous experiments (Chafe 1994, 1995a; Chafe and Ananías 1996).

The relationships between the change in S_{vi} and changes in shrinkage and rate of moisture loss were similar to those for changes between 5X10 cm and smaller samples as shown in Figures 3c to 3e: ΔS_{vi} was negatively related to ΔS_{wo} (although only at P=-0.12) and ΔE_{12r} and positively related to ΔS_{to} (Figs. 6c to 6e).

Figure 7 shows the actual shape of cross-sections of dried 5X10 cm samples, shrinkage being multipled by four to facilitate comparision. While there is some variation at preheating temperatures of 50 and 70 C, at 90 C, for all grain conformations, shrinkage in width was greater than that of controls, while shrinkage in thickness was less. This is in accordance with

Figure 6 which shows that the greater the shrinkage in width and the less the shrinkage in thickness, the lower the internal checking.

These results elaborate those of Chafe (1995a), who observed a negative relationship between internal checking and each of volumetric and tangential shrinkage; he suggested, therefore, that strategies to increase shrinkage, and thereby reduce checking, might be employed. The current experiment suggests that that approach was only half right. Figures 3, 6 and 7 show that while shrinkage in width is to be encouraged, shrinkage in thickness should be reduced.

The most significant indicator of a reduction in internal checking overall, however, was an increase in the drying rate. This is because, although the reduction in S_{vi} was also highly correlated with changes in shrinkage (Figs. 3, 6), shrinkage was highly correlated with increase in the drying rate as well. When change in S_{vi} was regressed simultaneously against changes in shrinkage and drying rate in best sub-sets multiple regression analysis for all 5X10 cm data, it was highly corrlelated with ΔE_{12r} at P=-<0.0001 but not at all with either shrinkage in width or shrinkage in thickness. A similar result was obtained when only data for 90°C was considered. When differences between 5X10 cm control samples and the smaller samples were similarly analysed, δS_{vi} was correlated with δE_{12r} at P=-0.0001 and only with δS_{to} at P=+0.02. Both these regressions were corrected for any influence of associated changes in A_{pvg}, S_g and M_i by the inclusion of these properties in the analyses.

Thus, the pre-eminence of permeability, as reflected here by drying rate, in quantifying internal checking would seem similar to its role in collapse development, and so supports the proposition of internal checking as an extension or special manifestation of collapse. Because of this, the reference to two 'forms' of collapse would appear justified: (1) 'external collapse', or that collapse which is manifested externally by surface and cross-sectional deformation of the timber, and (2) 'internal collapse' or that manifested by internal checking.

CONCLUSIONS

The reduction in internal checking achieved by the use of smaller dimensioned material, or by preheating the material when green, can be attributed very largely to the increase in drying rate so achieved. With preheating, the increased drying rate is consistent with an increased permeability. A further consequence of increased drying rate is, for 5X10 cm material, increased shrinkage in width and a decreased shrinkage in thickness. It is anticipated that preheating and/or the use of smaller dimensioned material, coupled with appropriate drying regimes, could very substantially reduce, and possibly eliminate, internal checking in collapse-prone species.

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Figure 1. Control cross-sections of mainly tangential grain orientation showing internally checked 5X10 cm sample (left) and matched, 5X5 and 2.5X10 cm samples without checks.

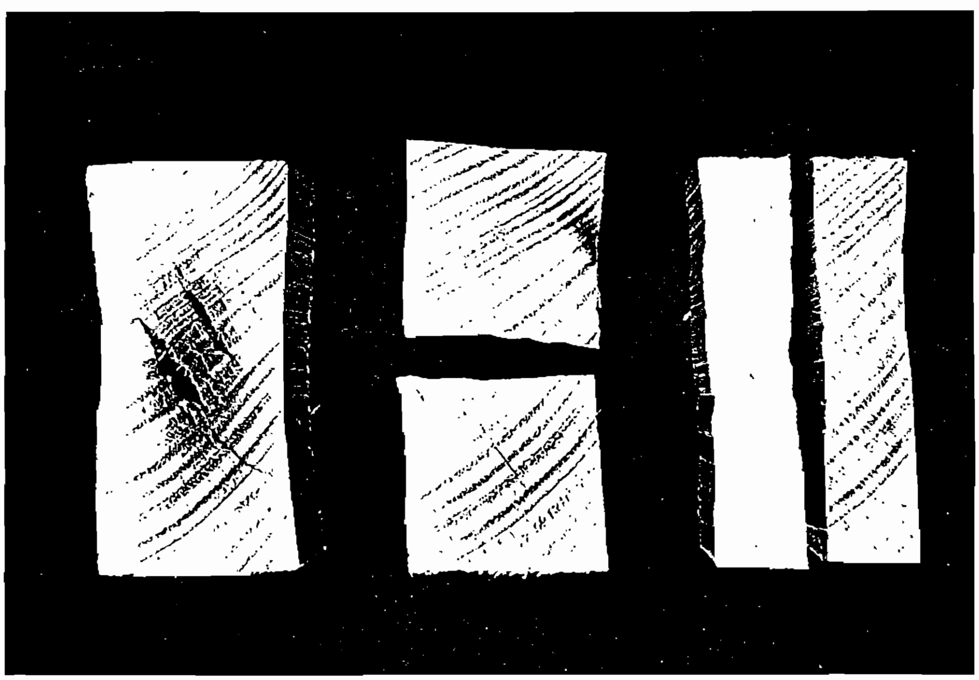

Figure 2. Control cross-sections of intermediate grain orientation showing internally checked 5X10 cm sample (left) and matched, 5X5 and 2.5X10 cm samples largely without checking but with evident external collapse.

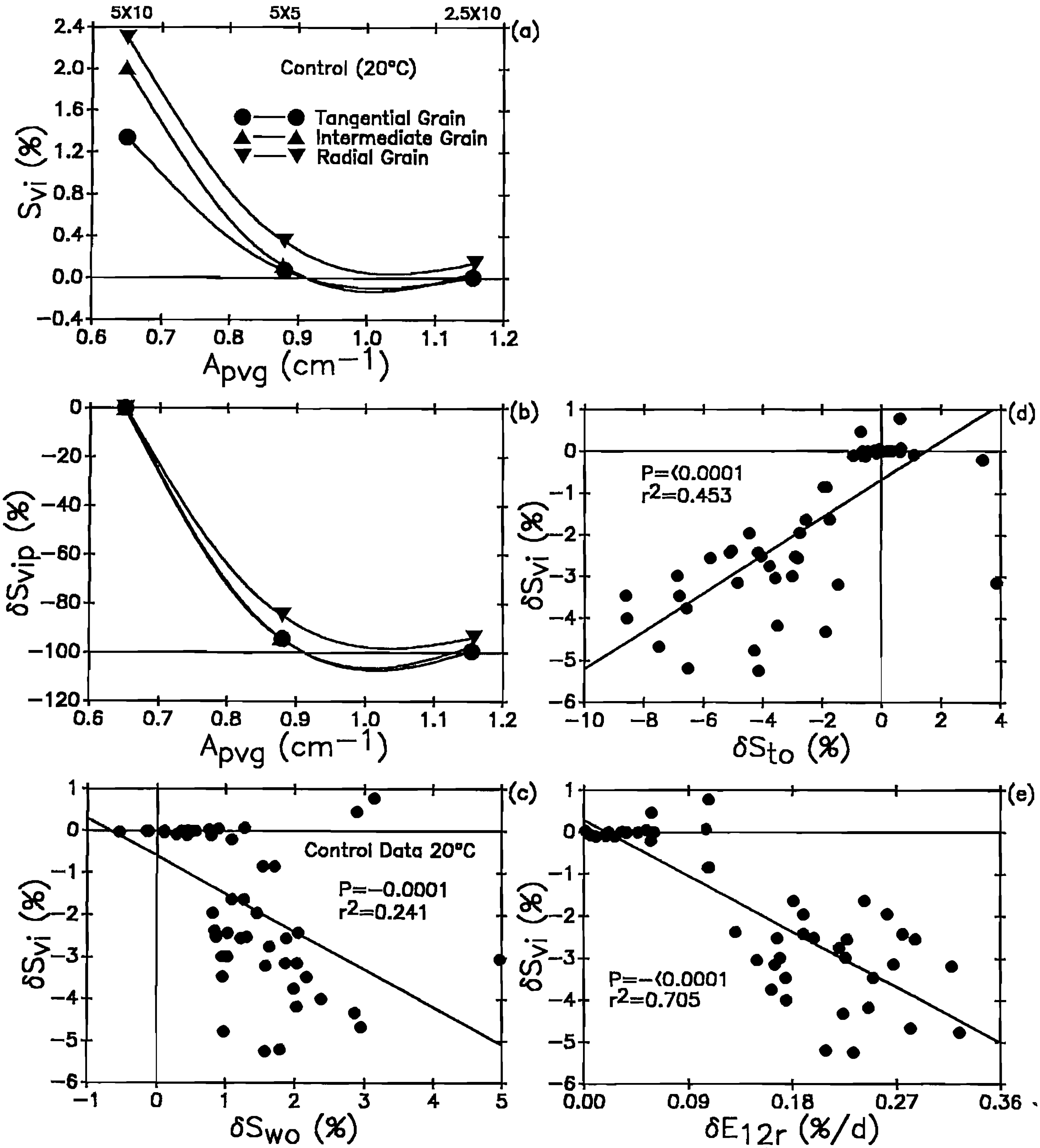

Figure 3. Control data. (a,b) Average internal checking (S_{vi}) and average percentage difference in internal checking from 5X10 cm samples (δS_{vip}) plotted against sample area per volume green (A_{pvg}). Corresponding sample dimensions indicated above graphs. (c,d,e) Difference in internal checking (δS_{vi}) between 5X10 and both 5X5 and 2.5X10 cm samples plotted against difference in shrinkage in width (δS_{wo}), difference in shrinkage in thickness (δS_{to}) and difference in rate of moisture loss (δE_{12r}), respectively. P=probability.

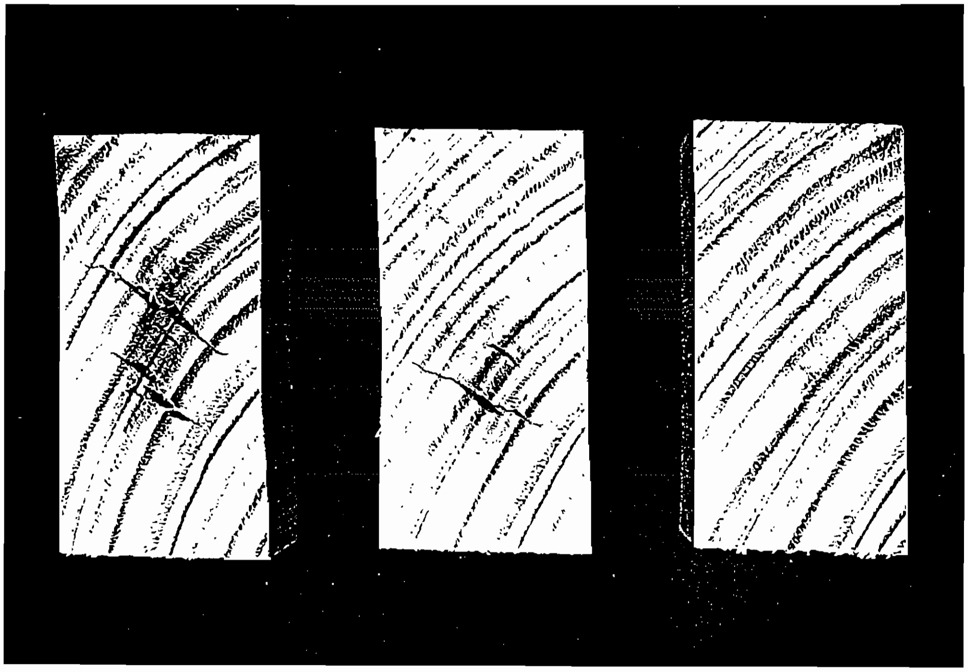

Figure 4. Five by ten centimetre cross-sections of intermediate grain orientation showing internally checked control (left), 70°C preheated sample (centre) with less checking, and 90° preheated sample without checking.

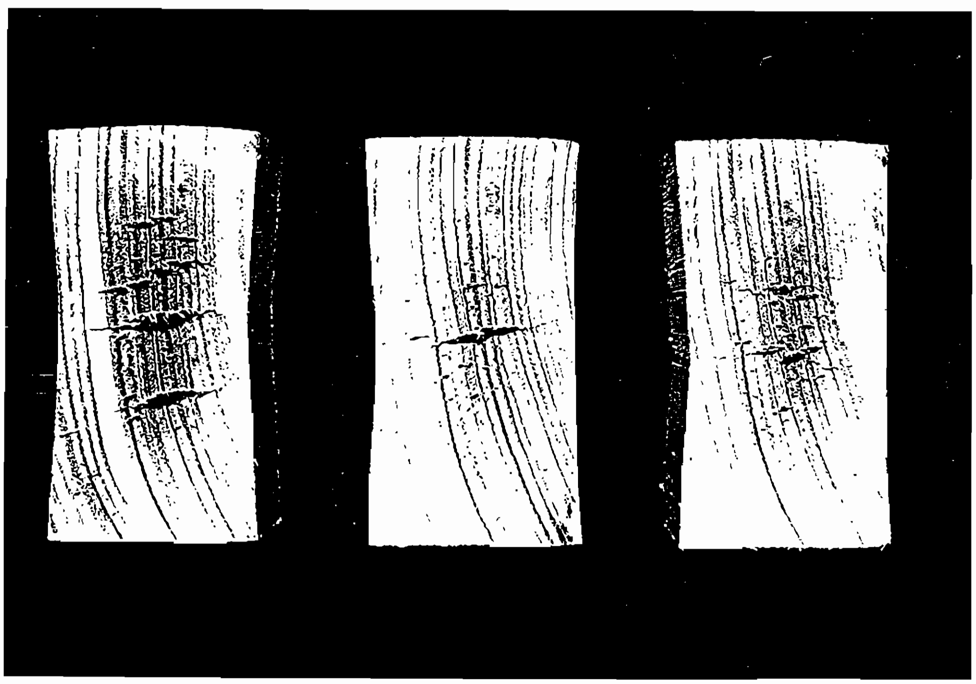

Figure 5. Five by ten centimetre cross-sections of tangential grain orientation showing internally checked control (left), 90°C gradually preheated sample (centre), and 90°C gradual preheated extended sample, both of which show reduced checking.

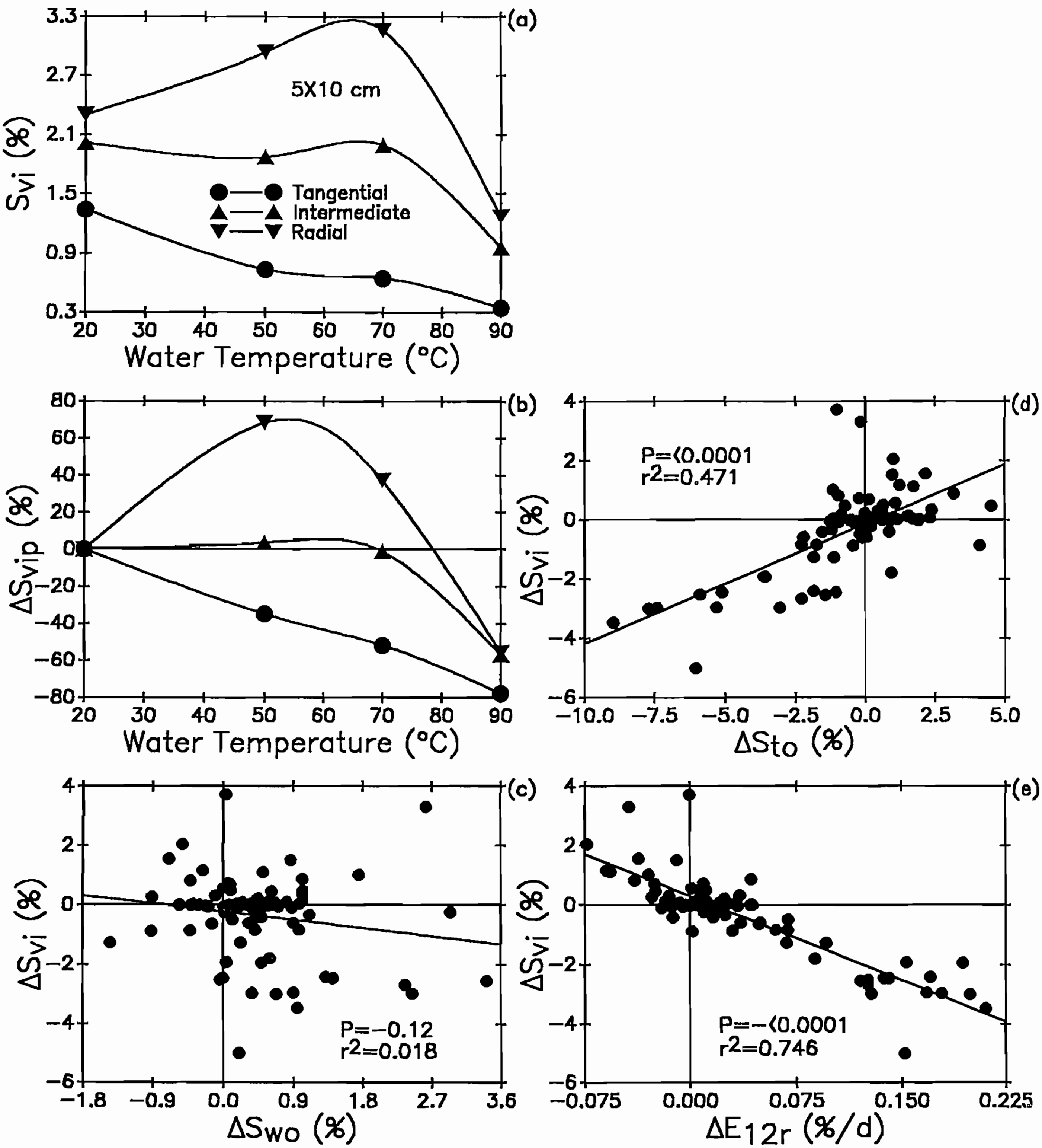

Figure 6. (a,b) Average internal checking and average percentage difference in internal checking from control (20°C) (ΔS_{vi}) plotted against pretreatment water temperature. (c,d,e) 90°C. Difference in internal checking from control (ΔS_{vi}) plotted against corresponding difference in shrinkage in width (ΔS_{wo}), difference in shrinkage in thickness (ΔS_{to}) and difference in rate of moisture loss (ΔE_{12r}), respectively.

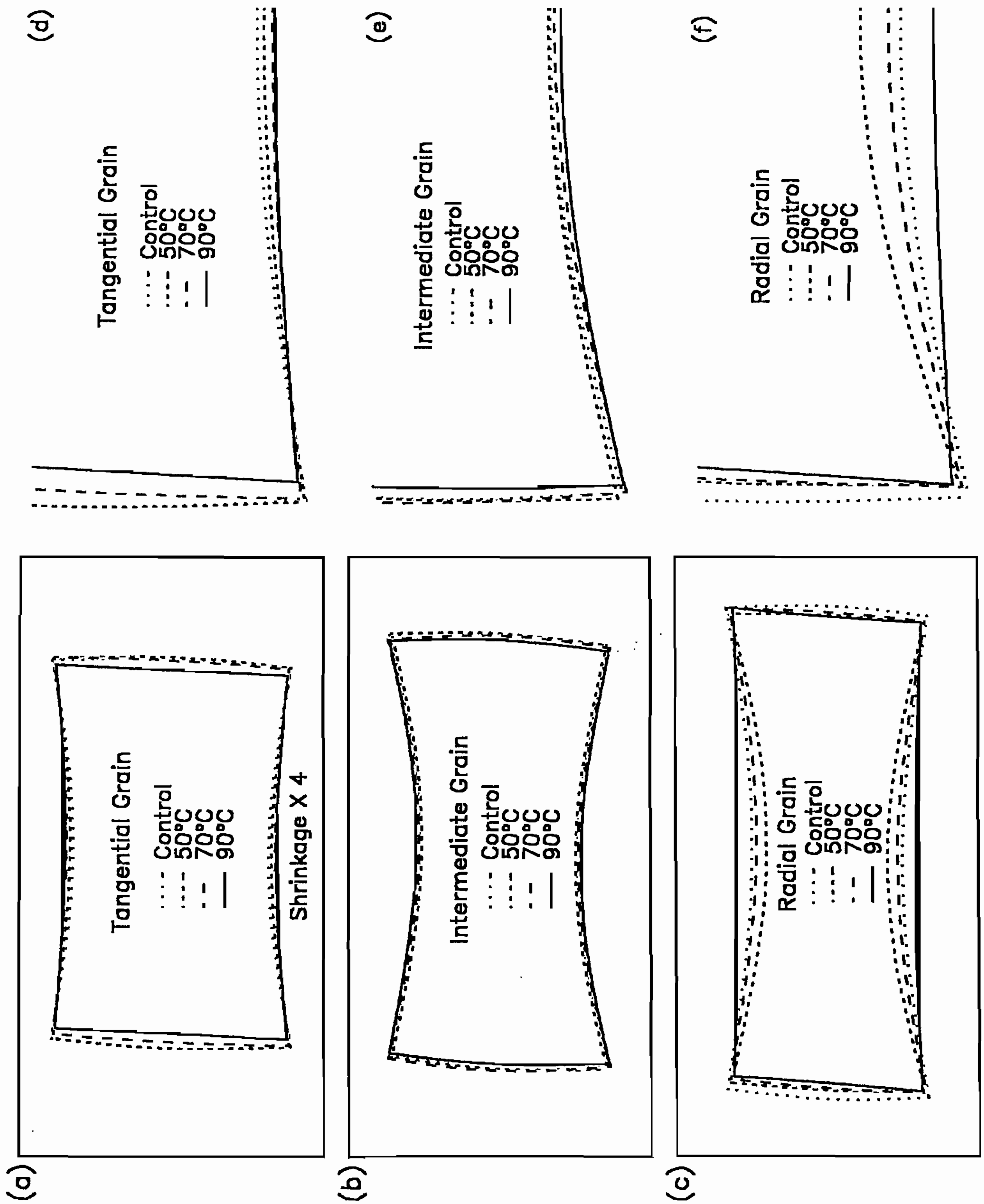

Figure 7. (a,b,c) Average shape of dried samples for tangential, intermediate and radial grain orientations for control and after preheating at 50, 70 and 90°C. (d,e,f) Enlagement of one quarter of the dried areas to allow clearer comparisions of shrinkage. Shrinkage multipled by four times.

Benefits to the Industry from Knowing Internal Log Information
- a discussion paper

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Abstract

The importance of obtaining internal log information and various benefits this information can bring to the sliced-veneer and timber industry are discussed in this paper.

Introduction

The future world demand for wood will increase in the long term as a result of:

1) Shortage of logs:
   a) continuing pressure from the conservation movement to reduce the amount of forest resource available to the forest products industry;
   b) a limitation on the amount of sustainable land available for plantations in the future.
2) Increasing demand for wood materials:
   a) rising population (the current world population is over 5 billion and this is doubling every 50 years. The per capita consumption of wood remains constant at about 0.7 m^3 per annum);
   b) higher incomes in many parts of the world therefore more consuming power.

At the same time, the forest products industry is facing a changing resource, characterised by an increasing proportion of smaller and fast-grown logs delivered to the mills, and increasing competition from the non-wood product industries.

To cope with this situation, one approach the forest products industry can take is to optimise the utilisation of log resources and the usage of the products produced. The Australian hardwood sawmilling industry has recognised that value-adding is the path leading to its survival and success in the long term. The hardwood industry has been under increasing pressure to reduce its use of the native eucalypt forests; it is in strong competition with the softwood industry in the structural product market.

Optimal utilisation of log resources involves two aspects, and I believe that it will offer:

(1) Improved log grading and optimal log allocation - logs are accurately graded and correctly allocated to the right mills to assure their best end use. This approach appears to be particularly needed by hardwood mills that do not have integrated log processing;
(2) Optimal log processing.

As a key step to improved log grading, optimal log allocation and optimal log processing, both external and internal information of logs must be identified and quantified with an efficiency acceptable to the industry.

Importance of acquiring internal log information

The cost of hardwood raw material accounts for 30% of the price of the end product (pers. comm. G. Waugh). Improving both grade and volume recovery by using improved technology therefore has significant implications for mill profit. It has been realised for a long time that knowledge of the presence, type, and size of internal defects in logs, followed by optimal log conversion based on this knowledge, leads to an increased value yield (Adkins et al., 1980; Chang and Guddanti, 1993; Harless et al., 1991; Peter and Bamping, 1962; Pnevmaticos et al., 1974; Pnevmaticos and Mouland, 1978; Richards, 1977; Richards et al. 1979, 1980; Steele et al., 1994; Tsolakides, 1969; Wagner and Taylor, 1975). For example, Steele et al. (1994) found by simulated sawing that optimum sawing orientation of 24 red oak logs gave about 10.1% increase in sawn timber value for both live and grade sawing over sawyer sawing, and that a higher value increase from optimum sawing orientation was achieved with better grade logs, although the difference was not statistically significant due to a large variance between the value yields at each orientation. It has also been demonstrated that accurate knowledge of growth rings in logs can help veneer producers to decide the best flitching and slicing options to increase veneer value (Schmoldt et al., 1996).

Several scanning methods initially developed for other fields such as medical diagnostics can be adapted to nondestructively detect log internal defects. Since the early 1980's, forest products researchers have been studying, and investigating the potential and industrial feasibility of these methods, as reported by Schmoldt (1992). Among these methods, X-ray CT-scanning is probably the best in terms of the resolution and contrast required in feature recognition. The Australian effort in developing an X-ray CT-scanning technology for the veneer and timber industry, the Glass Log Project (Davis et al., 1993), has become well-known both within Australia and overseas.

Relatively fast progress has been made in determining the external geometry of logs and the technology is now commonly used in softwood timber industry. However, due to more technical difficulties, it will take a longer time to achieve satisfactory and practical methods to quantify internal defects in both logs and sawn timber. Until now, no industrial technology for detecting individual internal defects in logs is commercially available. The eventual commercialisation of such a technology will depend on its technical performance and the amount of profit mills can gain from using it.

What benefits the internal log information may bring to the industry

Solid wood

- **Accurate log grading:** Current hardwood log grading in Australia, like in many other parts of the world, is based on visual assessment of log dimension, log form, and the type, size and distribution of various defects which are visible on the log surface. Visual grading has two problems. Firstly, external defects are not always a reliable indicator of internal defects, especially in larger logs. Thus it is impossible for even highly experienced log graders to make correct judgements on internal defects on every occasion. This problem is inevitable as long as visual grading continues to be practised. The second problem is associated with human performance such as lack of experience, subjectivity in making a judgement, insufficient care, and an urge to grade as many logs per unit time as possible. Both problems result in an unnecessary loss of raw material and productivity because the logs are processed in a way which does not match the raw material. An industrial log scanning technology, for instance based on X-ray CT-scanning methodology, will provide the internal log information needed for accurate log grading as well as consistent grading performance so that these two problems can be effectively solved.

To supply mills with logs correctly graded according to the existing log grading rules is one issue; to develop appropriate log grading rules or segregation criteria is another. To supply the mills with logs that satisfy their demands is yet a third issue. These three issues should not be confused with one another. The availability of internal log information will enable only the first two issues to be addressed.

- **Optimal log allocation:** With external and internal log information, log owners can determine by using various computer programs the optimal usage or the best potential of each log. Log owners will have a far better idea of what logs they have and how much they are worth. Logs can be sent to where their value can be best recovered. In addition, mills will have an opportunity to purchase logs which suit their equipment and product requirement.

- **Suggest cutting pattern(s) for primary sawlog conversion:** With external and internal log information (such as knots and decay), the sawyer can decide with the assistance of various computer programs how to orientate each log, what sequence to follow to convert each log, and what size of boards to cut from each log in order to meet the requirement of the mills in producing various products. (The mills will have the choice of either simply maximising the value return of their logs, or finding an economically sensible combination of product grades and dimension in conjunction with an economically sensible conversion process). Internal log information can be generated either before logs are delivered, or at the mills.

- **Detect internal checks during and after drying:** Some species of eucalypt are prone to internal collapse checking during drying. Other hardwood and softwood species can also develop internal checking during drying. A scanning technology which is able to detect the presence of internal checks will greatly enhance the screening process, giving assurance that the dried timber sent to make appearance products, such as mouldings and furniture components, are free of sizeable internal checks. It will also be a very useful research and monitoring tool to help us understand and control the development of internal checks during drying.

- **Detect wetwood in logs or unseasoned boards:** Wetwood is relatively common in Australian hoop pine. It dries much more slowly than normal wood. As a result, patches of wet zones appear in seasoned boards. One approach to handle the wetwood problem is to identify its location either in logs or in sawn boards and to segregate it from the normal wood. Higher moisture content of wetwood makes the identification of wetwood relatively easy when using such method as X-ray CT-scanning and NMR.

Sliced-veneer

- **Log selection**: With external and internal log information, mills can use computer programs to assess the grade, quantity, and size of sliced veneer that each log can produce. The mills then can use this data together with information on the raw material cost and the production cost to determine the profitability of slicing each log. Hence an economic criterion (threshold) can be established to select logs profitable for veneer slicing. Actual profit for each veneer log can also be determined. The mills can then be confident that the logs sliced will yield a profit and not a loss. They will also have a clear indication of how much profit each veneer log will produce.

- **Optimal flitch preparation and appropriate slicing method:** Knowing the types of defects, their size and distribution, the mills can find various options for flitch preparation and slicing methods by using computer programs, and then decide how to prepare flitches and how to slice each flitch.

- **Control of grain pattern:** The internal log data such as those generated by the X-ray CT-scanning method contains information on growth rings and thus can be used to reveal wood grain patterns in any specified plane within a log. This aspect of internal log information enables the mills to determine how to orientate a flitch and what method to use to slice this flitch in order to generate the wood grain pattern which is more valued or demanded by the market.

Plantation management

- **Monitoring the incidence of decay:** More and more eucalypt plantations will be established in Australia for sawlog production. In order to produce a higher proportion or a wider band of clearwood and to minimise the size of the knotty core in tree stems, mechanical pruning is required at an early stage of tree growth. This is especially the case for species which do not self-prune well such as *Eucalyptus nitens*. The branch stubs and pruning wounds are easy invasion points for fungi. Concern has been expressed by Tasmanian foresters of the possible close association between increased incidence of decay in tree stems and mechanical pruning. Non-destructively obtained information on decay in living trees will help foresters to assess and modify their forest management scheme, and consequently to produce sawlogs with a quality the trees are managed to provide. A portable X-ray CT-scanner is already available in Australia for non-destructive detection of decay and termite infestation in electricity power poles and standing trees (Davis et al., 1995).

Summary

Studies have shown that knowing what is inside logs and applying this knowledge during log conversion can significantly improve the value yield of the logs. There has been a continuing effort in Australia, Europe, and North America, to develop a non-destructive log scanning technology for the forest products industry. The forest and forest products industries can benefit from such a technology through various applications as briefly discussed in this paper. The Australian effort in developing the X-ray CT-scanning technology for the veneer and timber industry should be actively encouraged. Industrial log scanners will mostly likely become more affordable with time as the manufacturing cost drops and more mills start to use them. Development of various computer programs utilising

the internal log information is definitely needed in Australia to match the X-ray CT-scanning R&D work.

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KILN DRYING RATES OF HARDWOOD SAMPLE BOARDS PLACED IN OR HUNG ADJACENT TO STACKS

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ABSTRACT

The drying rates of pairs of matched sample boards, placed either in stacks or suspended in adjacent kiln sidespaces, were monitored during kiln drying from below 25% moisture content to final values of 8-12%. All sample boards were weighed two or three times during the course of rapid drying at temperatures of 70-100°C. Results are given for several species of medium density, tropical hardwoods.

In most cases, differences in moisture content between pairs of matched sample boards after partial or full drying were of the order of 1% or less, thereby making the kiln sidespace suspension of sample boards a valid alternative to conventional in-stack practice. This conclusion is considered to be a result of comparable rates of drying at the two selected positions, not to approaching wood equilibration.

BACKGROUND

The *ad hoc* investigation described here resulted from the author's recent consultancy in Fiji to commission new kilns and to accelerate, if possible, drying schedules originally developed by CSIRO Division of Forest Products, over more than a decade in the 1960s and 1970's, for the Department of Forestry, Fiji (Alston 1982).

It soon became evident that a quick and valid alternative was needed to the traditional, time-consuming practice of removing and replacing sample boards placed inside packs of timber when kiln temperatures are in excess of 60°C at time of entry. One possible approach (raised by Professor Robert Little during a talk to the Institute of Wood Science on 2nd August 1994), was to stand sample boards against, or hang them from kiln walls. When the former did not work because of excessive take-up of moisture through the surfaces of boards, as a result of condensate running down the walls and congregating on uneven concrete hobs, the validity of hanging sample boards from condensate return pipes running along both side of the stack was examined. Simple frames were constructed for this purpose.

MATERIALS AND METHODS

Timber Species

The following species, with relevant properties listed, were used in this reported part of the overall study:

Species	Density (12% m/c) kg/m^3	Shrinkage % Tang.	Shrinkage % Rad.
Kaudamu (*Myristica spp.*)	580	7.8	4.0
Kauvula (*Endospermum macrophyllum*)	480	3.6	1.9
Mixed Light Hardwoods (8 or more *spp.*)	550-700	3.9-6.0	2.5-3.5

Preliminary air drying of packs

After sawing and nominal pressure impregnation with a waterborne preservative, hardwood timber is manually strip stacked into square-ended packs, 6 m long by 1 m wide by 1 m high. Stickers are currently 17 mm thick to maximize kiln holding capacity.

Air drying is extremely fast at a site bordering the Pacific Ocean. During the dry season, the average drying time from green to fibre saturation point for most species is six weeks for 25 mm thick timber and approximately twice that for 50 mm. These times are approximately doubled during the wet season. Subsequently, the timber dries to about the climatic equilibrium moisture content values of between 15 - 17%, depending on the season.

Selection and preparation of sample boards

After each pack was selected for drying, a 3 m or longer board was removed from its geometrical centre, with the aid of a fork lift loader. A 400 mm length was cut and discarded from the end of the board. Subsequent cross-cuts were made for: a 25 mm wide average moisture content (m/c) section; a 450 mm long sample board; 25 mm wide average and distribution m/c sections; another 450 mm long sample board; and a 25 mm wide average m/c section. All samples were then weighed on digital balances to resolutions of 0.1 gm for sample boards, and to 0.01 gm for m/c sections that were then oven dried. Both ends of sample boards were sealed with two coats of acrylic paint without delay, and wrapped in plastic until required later.

Kiln Stacks

Each kiln charge consisted of a 2-pack wide by 3-pack high, square-ended stack, with dimensions of 6 m long x 2 m wide by 3 m high. Its holding capacity ranged from 25-30 m^3 for timber thicknesses of 25-50 mm respectively, separated by mostly 17-20 mm thick stickers. Packs to be kiln dried were mostly selected from air drying yards on the basis of commercial requirements. Packs were transported and loaded on kiln trucks by fork lift loader.

Placement of sample boards

(a) In the stack

For convenience, sample boards were inserted into the stack before it was moved into the kiln. One sample board was placed in each of the six packs, near opposite ends and at mid-length. Generally, sample boards were put in the second row from the edge, with a dummy board in the edge row. They were a neat fit between adjacent stickers.

(b) Hanging from frames

Simple frames were constructed for hanging sample boards horizontally in both kiln sidespaces. They consisted of a 450 mm length of 100 by 50 mm timber to which two lengths of fencing wire were rigidly attached for looping over condensate return pipes located near the top of the kiln. Fine wires loosely attached to each end of sample boards incorporated loops for hanging over the ends of the piece of timber for quick and simple retrieval for weighing and subsequent replacement.

Frames were suspended at a distance of some 400 mm from the kiln walls and 800 mm from the sides of the stack. Sample boards were hung 1800 mm above the kiln floor. Three frames, equally spaced along the length of the kiln, were provided on each side of the stack. Matched pairs of boards were placed on the same side of the stack, though not necessarily opposite each other along the length of the stack. This is not regarded as a possible confounding factor because of the good uniformity of air velocity and temperature over the face of the stack. Sample boards were hung from frames just before or after moving the stack into the kiln.

Measurement of sample board moisture content

On average, sample boards were weighed two or three times during the process of kiln drying, including final conditioning, and their moisture contents calculated. Some boards were removed from the kiln during the early and middle stages of drying for sectioning and oven-dry m/c determination, but the bulk of them after drying and final conditioning.

The following sections were cut from all kiln dried sample boards: a 25 mm wide average m/c section, 25 mm from a coated end (to check the effectiveness of end coating); 25 mm wide average and distribution sections from the centre length of the sample board; and a 13 mm wide drying stress section from the same position. Moisture contents were determined by the oven dry method.

Kiln drying settings

Variable speed fan motors installed in the kilns provided recommended air velocities for hardwoods of 1.5 to 1.8 m/s through the stack to be easily attained for 25-50 mm thick timber. By-passing of circulated air was minimal because of permanent pairs of baffles installed above the stack and at each end of it. Direction of air circulation was automatically set for 2 or 3 hourly reversals.

Air velocity over sample boards hung from frames in the side spaces was 1.6 m/s with a range of 1.4 to 2.0 m/s in both the forward and reverse directions of air circulation, and are comparable with values over sample boards placed in the packs.

The temperature control system, including automatic vent operation, enabled drying conditions to be precisely controlled over a wide range of temperature and relative humidity. The extremely well-sealed kiln, in conjunction with large diameter humidifying pipes, ensured small wet bulb depressions for final conditioning were attainable at dry bulb temperatures of 80^{0}C or more. The internal fan motors are rated for continuous operation at 100^{0}C.

RESULTS AND DISCUSSION

25-50 mm thick kaudamu

Table 1 gives timber sizes, kiln drying parameters and moisture content data for groups of 25, 37 and 50 mm thick kaudamu sample boards used in individual kiln drying runs, after their preliminary air drying to mean values of 16-21% m/c.

Each thickness was dried in a separate run to a final moisture content determined by its destination and end-use. Locally, 8% m/c is required for blockboard manufactured on site, and 16% m/c for general building purposes. For export, plastic wrapped bundles of timber are supplied at 8% or 12% m/c, as ordered.

By way of comparison, kaudamu has similar density and shrinkage values to "ash" type eucalypts: mean density of 580 kg/m^3 at 12% m/c *c.f.* 630 kg/m^3 for mountain ash; and respectively, tangential shrinkages of 7.8% and 7.1%, and radial ones of 4.0% and 3.7%. It also exhibits collapse to the extent that 4 to 6 h reconditioning is recommended for 25-50 mm thick timber.

Checking is not usually a problem in 25-38 mm thick material, but can be serious in wide 50 mm thick stock, even during air drying. For that reason, the CSIRO developed drying schedule of 70/20°C (dry bulb temperature/wet bulb depression) for below 25% m/c was followed for the 50 mm thick timber. In spite of taking that precaution, there was considerable fall-down in the entire stack of this timber at the end of drying and final conditioning, on account of surface and end checking, particularly in wider boards. It is not known how much of the problem was due to worsening of pre-existing checks after air drying or development of fresh checks during kiln drying.

Drying conditions of 90/15-20°C for 25 mm and 38 mm thick boards, rather than the CSIRO recommended 70/20°C, boosted drying rate without causing degrade, an outcome previously reported for alpine and mountain ash boards dried at elevated temperatures below fibre saturation point (Christensen, 1984).

In Table 1, the 'Initial M/C' column gives the initial m/c of the six 'in-stack' sample boards plus their mean m/c value. The column headed 'Stack-Hung M/C Diff - Initial' shows the small initial differences in m/c between the matched pairs of sample boards. The '+' sign indicates the initial m/c of the 'in-stack' sample was higher than that

TABLE 1. Drying and moisture content data for 25-50mm thick kaudamu sample boards

Thick-ness mm	Width mm	DBT °C	WBD °C	Dry Time h	Initial M/C %	M/C drying change %	Stack-Hung M/C Diff. Initial %	After Dry. %
25	150	90	15	7	17.8	8.5	+0.6	+0.4
					13.7	4.5	0.0	+0.8
					19.4	6.2	- 0.1	-0.3
					19.9	6.7	+0.1	-0.7
					25.2	10.4	-2.6	-0.5
					22.4	9.6	+1.0	+0.7
				Mean	19.7	7.6	0.7	0.6
38	100-150	90	20	10	16.3	7.5	+0.3	-1.0
					17.1	6.4	+0.2	+0.2
					15.8	6.7	-0.7	-0.7
					15.7	5.5	0.0	-1.0
					16.4	6.5	-0.7	-0.8
					16.7	7.2	-1.4	0.0
				Mean	16.3	6.6	-0.3	0.6
50	100-250	70	20	8	22.8	5.0	+0.5	+1.5
					22.2	5.7	0.4	-0.2
					23.7	7.1	-0.1	0.0
					19.6	4.8	+0.4	+0.4
					17.8	3.8	+0.1	+0.7
					18.8	3.4	-0.4	+0.5
				Mean	20.8	5.0	0.3	0.6

of the 'hung' one. The negative sign indicates the opposite effect. Likewise, the 'M/C Diff. After Dry.' column gives the relative m/c differences after drying between matched pairs of sample boards located in stacks and hanging in kiln sidespaces.

Mean m/c drying changes of 7.6%, 6.6% and 5.0% are shown in Table 1 for timber thicknesses of 25 mm, 38 mm and 50 mm after drying for 7, 10 and 8 hours respectively. The actual mean m/c values at that stage of drying were 12.1%, 9.7% and 15.8% for the three respective thicknesses. On the other hand, the equivalent wood equilibrium moisture contents (EMCs) of the drying conditions shown are either 5% or 6% for the three thicknesses.

Because the actual wood moisture contents are well above the equivalent equilibrium values of the drying conditions, it is considered that the relatively small m/c differences between the 'in-stack' and 'hung' sample boards at the stated drying times are due to comparable rates of drying at the two sample board positions, and not to approaching equilibration of the wood. Even for the largest individual reductions in m/c during drying of 8.5-10.4%, the corresponding m/c differences between the pairs of matched sample boards were still only 0.4-0.7% for all three thicknesses; and they are similar to the initial differences which were, on average, less than 0.5% m/c. Furthermore, when the sign (+/-) of the m/c changes is taken into account, there is no regular pattern of faster or slower rates of kiln drying at either of the two sample board positions.

25 mm thick kauvula

Drying conditions and moisture content data for 25 mm kauvula are given in Table 2. These results are included because they show that two pairs of sample boards at relatively high initial moisture contents still did not exhibit real differences in m/c after drying as a result of being placed 'in-stack' or 'hung' alongside the stack. In other runs, not reported here, there were isolated examples of this behaviour with the same outcome. Values for one pair of sample boards are not included because of initial weighing errors.

The initial mean m/c and change in m/c during drying are comparatively large because they were boosted by the two pairs of sample boards already mentioned. (It is understood that they, and other high m/c sample boards detected in other runs, came from packs virtually sitting on the ground in poorly drained areas; and were probably taken from rows near the bottom of packs instead of mid-height, as recommended.) Once again, the mean m/c difference between 'in-stack' and 'hung' sample boards after the stated drying time was only 0.8% m/c. While the sign of the final m/c difference between 'in-stack' and 'hung' matched pairs of sample boards does not indicate a kiln positional effect, any conclusion is subject to the consideration that three out of the five pairs of sample boards reached final moisture contents approaching the equivalent wood EMC

TABLE 2. Drying and moisture content data for 25 mm kauvula sample boards

Thick-ness mm	Width mm	DBT °C	WBD °C	Dry Time h	Initial M/C %	M/C drying change %	Stack-Hung M/C Diff. Initial %	After Dry. %
25	100-150	85	15	15	15.8	9.8	- 0.2	-0.4
					16.7	10.5	+ 0.5	-0.8
					39.2	23.7	- 6.3	+0.2
					27.0	18.3	-1.6	-1.4
					18.5	11.5	+0.9	+0.8
				Mean	23.4	14.8	1.9	0.8

of the drying conditions of 6%. But this proviso definitely does not apply to the pair of sample boards at an initial m/c of 39.2% and a final one of 15.5%, when their difference in m/c was only 0.2%.

25 mm thick Fijian mixed light hardwoods

Drying conditions and moisture content data for two stages in the kiln drying of 25 mm Fijian mixed light hardwoods are given in Table 3. Specific species of sample boards used were not identified, but at least nine species are regularly processed at the plant. Additionally, some heavy hardwoods (930-980 kg/m^3) were detected in some packs by their slower rate of drying (extra 24 hours or more needed). Possibly one pair of sample boards in this run fell into that category.

The initial moisture contents listed for the second stage of drying are the original ones (less two samples sectioned for oven dry m/c values), and both sets of m/c drying change results are derived from them. There was a wide variation in the drying rate of individual sample boards during the first stage (2:1), when their mean m/c fell from 15.5% to 11.3% (range: 9.4-13.5%). This flattened out during the second stage, which reduced the mean m/c to 8.1% (range: 7.0-9.0%). The equivalent wood EMC of the drying conditions was 5-6%.

The 'stack-hung m/c differences' show a relatively slight but definite tendency for the "in-stack' sample boards to dry faster than their matched 'hung' ones. This was more pronounced over the second or approaching equilibration stage of drying, contrary to

TABLE 3. Drying and moisture content data for 25 mm thick Fijian mixed light hardwoods

Thick-ness mm	Width mm	DBT ^{0}C	WBD ^{0}C	Dry Time h	Initial M/C %	M/C dry-ing change %	Stack-Hung M/C Diff. Initial %	
							Initial %	After Dry. %
25	75	90	15	3	18.0	4.5	+ 0.2	+ 0.3
					15.9	5.4	+ 0.2	+ 0.3
					16.4	4.4	- 1.0	- 1.6
					12.5	3.1	- 0.3	- 0.8
					16.2	5.0	- 0.8	- 1.4
					14.2	2.4	0.0	- 0.8
				Mean	15.5	4.1	0.4	0.8
		90	20	4	15.9	8.8	+ 0.2	- 0.8
					16.4	7.0	- 1.0	-2.1
					12.5	5.5	- 0.3	- 1.5
					16.2	7.5	- 0.8	- 1.4
				Mean	15.3	7.2	0.6	1.5

expectations. From a practical point of view, it is claimed that the difference does not invalidate the contention that both positions are equally acceptable for the placement of sample boards.

Sample board end coatings

Oven dry m/c values obtained from sections, cut 25 mm from one end of all sample boards after drying, showed that the application of two coats of acrylic paint before kiln drying was an effective end seal. The difference in m/c between sections cut 25 mm from one end and at the centre length of sample boards was generally of the order of 1-2%. A relatively few exceptions appeared to be due to a less than optimum thickness of end coating. Thus, the drying of most sample boards would be characteristic of the behaviour of long boards.

CONCLUSION

For 25-50 mm thick hardwood boards, previously dried to below fibre saturation point, the results reported indicate that the placement of sample boards in stacks or hung in the adjacent sidespace is virtually equivalent in terms of drying rate.

In most cases, differences in the moisture content of pairs of individual sample boards were 1% or less. This evidence leads to the conclusion that comparable rates of drying were obtained at the two selected positions in the kiln.

At the reported end-point of drying, wood moisture contents were sufficiently elevated above the equivalent wood equilibrium moisture content of the drying conditions to disregard the effect of wood equilibration as a significant factor in the outcome.

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UTILISATION OF *PINUS RADIATA* RESIDUES FOR PROCESS ENERGY AND CARBON

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ABSTRACT

Fluid bed carbonisation with heat recovery integrates well with sawmilling and kiln drying operations since it has the potential to process the total residue production and to produce heat for kiln drying. The excess energy in the residues is converted into a charcoal product which can be more economically transported to markets since the mass is reduced to a small fraction of the original. The value of the charcoal product per unit of source material is significantly higher. In conventional carbonisation processes, the volatile by-products are not usually recovered and often present a major pollution hazard.

P. radiata residues in the form of green sawdust, woodchips, bark, planer shavings and shredded dockings were carbonised in an air fluidised bed. The yields of charcoal obtained were 20-22% of the wood feed calculated on an oven dry basis. Bark produced a higher yield of 36%. The yields obtained from fluid bed carbonisation compared favourably with pure pyrolysis where the same residues, after oven drying, were subjected to conventional carbonisation in the absence of oxygen in a rotary retort to give the maximum possible yields of charcoal. On this basis, fluid bed yields from the wood residues were 69-74% of that from pure pyrolysis. Bark yields were higher, at 79%.

INTRODUCTION

The pine sawmill industry in Australia produce kiln dried, dressed timber for structural and furniture grade use. The wood resource is derived from well established plantations with high growth rates producing good quality logs. The sawmills operating on plantation *Pinus* species have the largest log throughput in Australia. Typical residue production consists of bark from debarking operations, green sawdust, slabs and edgings from the breakdown sawing of the logs. In the dressing and sawing to length of the kiln dried timber, planer shavings, dry sawdust and dry dockings are produced. Where there is a woodchip export facility and a demand for the chips, the slabs and edging residues are chipped in either secondary chippers or primary breakdown saws with chipper-canter heads. Bark has a market for garden mulch and compost but the volume produced far exceeds demand. Where there is a nearby particle board manufacturer, the planer shavings are a valued feedstock. However, this residue is very bulky and transport costs are high. There are no significant markets for the green sawdust and dry dockings.

Almost invariably, the sawmills would use part of their wood residues to supply the energy demand for kiln drying and, in most cases, residue production exceeds its use for energy and for existing markets. Under these circumstances, the residues must be disposed of by landfill dumping or incineration.

A method of partial combustion of wood to produce charcoal and process heat energy has been developed by the Division of Forestry and Forest Products which could be used to process all the residue production into carbon and supply the heat requirements of the mill's drying kilns (Fung 1985). The system partially burns the wood in a fluidised bed where essentially the volatile byproducts of carbonisation are combusted leaving the carbon which is recovered before it has time to burn away. The system is flexible in that it could completely burn the wood, including the charcoal, to supply the maximum heat output. This is of advantage during the startup of the kilns from cold when the energy demand is maximum during the heating up of the cold charge of timber. When operating temperature is reached, the heat demand of the kilns falls. The CSIRO system, under this condition, could be operated to produce optimum charcoal yields and to reduce the heat output in line with the drop in demand. The byproduct charcoal could then be sold producing a profitable return on the unutilised residues. Some of the potential uses of wood charcoal are therefore discussed.

To evaluate the carbon production potential of the residues, the yields of carbon from each residue stream were determined using the CSIRO partial combustion method. As this method of carbonisation is rapid and some of the carbon produced invariably burns, the results were compared with the more ideal yields produced by pyrolysis in the absence of air. Pyrolysis type systems, such as batch carbonising kilns, are not suitable for energy recovery. The smoke generation by these kilns is difficult to control and can cause serious pollution problems. Although charcoal yields from pure pyrolysis would be higher, it has limited application with regard to processing the range of sawmill residues. Green wood residues require predrying which is a costly operation. The CSIRO fluid bed system however, is more tolerant to green wood feedstocks.

Some uses for wood charcoal

1. Fuel

Charcoal is a clean - burning, smokeless fuel with negligible sulphur and a high calorific value, typically 30 000 - 32 000 kJ/kg. This is three times that of green wood and approximately two thirds that of fuel oil. A market already exists as a recreational fuel for barbecues and charcoal grills. Charcoal fines can be made into briquettes which are compact to transport, easy to use and can be made cleaner to handle than lump charcoal.

2. Soil Conditioner

Charcoal is used in potting mediums. It improves the structure of various soils giving better drainage in heavy clay soils and better moisture holding capacity in sandy soils.

According to Kishimoto and Sugiura (1990), it helps to promote the growth and vigour of plants. Therefore, charcoal is used in wider applications for food crops, pastures, silviculture and lawns. Charcoal from bark and sawdust can be used for this application.

3. Metallurgical Carbon

Wood charcoal is a good source of metallurgical carbon. Its negligible sulphur and low phosphorus contents are extremely beneficial since these elements are a major cause of embrittlement of metals such as iron and steel. Brazil is the world's largest exporter of high grade pig iron. It manufactures some 10 million tonnes/year of wood charcoal for its important Iron and Steel Industry. Wood charcoal is also a very reactive carbon and because most commercial Australian wood species are low in ash content, the charcoal obtained from these can be relatively pure. A major use of wood carbon in Australia is for metallic silicon metal manufacture (Spratt and Brosnan 1990). Because of the high quality of the wood charcoal, the corresponding grade of silicon metal product is high.

4. Activated Carbon

Australia currently imports all its activated carbon requirements, most of which is used in gold extraction, water treatment, air pollution control, food, beverage and industrial processing. Wood based carbon is a good feedstock for activated carbon manufacture. It has been shown to perform exceedingly well in gold adsorption (Fung 1990) and the removal of blue-green algae toxins in town water.

5. Filler

Low cost wood carbon can be used as a filler for rubber and plastics products where a black colouration is required. It was found to have lower reinforcing characteristics than the more expensive carbon blacks for rubber products such as automotive tyres, but may have potential uses in other non- or low- strength applications (Fung and Nowak 1981).

EXPERIMENTAL METHOD

Source of Samples

Samples of the various residues were collected from Auspine's sawmill in Tarpeena, SA. The fresh samples collected were sealed in plastic to prevent drying. The selection made was representative of the production from the mill and was sourced from the following:

(a) Bark - from a ring debarker

(b) Green sawdust - derived from a "Chip-n-Saw" and gang sawing equipment. A mixture of sawdusts was obtained.

(c) Green chip - was a mixed sample from the "Chip-n-Saw" machine and from a standard chipper.

(d) Planer shavings - were sampled from the timber dressing operations

(e) Dry dockings - a shredding machine at the mill produced small chunky material from the dockings. The shredded dockings were sampled.

Moisture Content Determinations

Moisture content determinations were undertaken by oven drying the samples at 105°C for 20-24 hours. Grab samples were used for all the residues except bark in the following sample sizes: 100-140 g in the case of sawdust and chips, 60-90 g for shredded dockings and 20 g for shavings. Since there was a large variation in moisture content within the bark samples, bulk samples of 4-5 kg were used for moisture content determinations.

Carbonisation Studies

Carbonisation studies were conducted on split samples in both a small scale air fluidised bed and a rotary retort under oxygen free conditions.

a) Fluid Bed Carbonisation

A 100 mm diameter fluidised bed was used in the carbonisation trials on two litre batches of as received residue samples. The maximum temperature of carbonisation was 500°C. The charcoal produced was recovered from the bed and from a cyclone which collected charcoal fines.

b) Rotary Retort Carbonisation

The rotary carbonisation runs were performed on the other half of the matched samples which were first oven dried. The retort was heated at a programmed furnace heating rate to a final temperature of 510°C. At the end of the heating cycle, inert nitrogen gas was used to purge and blanket the retort contents while cold air was blown through the furnace to cool the outer walls of the retort. When the charcoal product cooled to 80°C it was discharged and weighed.

RESULTS AND DISCUSSIONS

Charcoal Recovery from the Fluidised Bed

The charcoal recoveries were calculated as the percentage ratio of the weight of charcoal obtained to that of the oven dried wood or bark charge. The oven dried weight of wood was calculated from the moisture content.

Table 1 shows that the average charcoal recovery for *P. radiata* wood was in the range 19.6 - 21.7%. *P. radiata* bark had the highest recovery of 35.5%. The high recovery from bark could be partly attributed to an intrinsically higher ash content than that of wood. Total charcoal recovery from green sawdust was 19.6% which was the lowest of the residues tested. Green woodchips produced a charcoal recovery of 21.5% which was greater than that of green sawdust and about equal to that of dry shavings of 21.7% and to shredded dockings of 21.5%.

TABLE 1. Fluid Bed Carbonisation - Charcoal Recoveries

SAMPLE	MOISTURE CONTENT (%)	CHARCOAL RECOVERY (%)
Green bark	59.1	35.5
Green sawdust	117	19.6
Green chips	120	21.5
Dry shavings	12.8	21.7
Dry dockings	16.6	21.5

Comparison of Charcoal Recovery by Pyrolysis

The pyrolysis of oven dried *P. radiata* residues in a rotary retort was carried out in the absence of oxygen. The charcoal recoveries are shown in Table 2. These recoveries were likewise calculated as the weight of charcoal expressed as a percent of the oven dried charge. Except for one set of sawdust carbonising runs, all the samples were oven dried at 105°C for 24 hours before carbonisation.

Compared with carbonisation in an air fluidised bed, pyrolysis under idealised conditions will obviously produce a higher yield of charcoal but the volatiles produced must be disposed of if not used. In fluid bed carbonisation, these volatiles are combusted in the bed and utilised for heat production. Some of the charcoal is also inevitably combusted within the bed which will reduce the yield. A comparison of charcoal yields between both methods are shown in Table 2 as a percentage ratio of the recovery of charcoal from the fluid bed to that from the rotary retort. Based on the runs conducted, the ratio is in the range 65 - 79% which shows a favourable yield of charcoal in the fluid bed.

TABLE 2. Rotary Retort Pyrolysis - Charcoal Recovery Comparison

SAMPLE	MOISTURE CONTENT (%)	Rotary Retort CHARCOAL RECOVERY (%)	FBed:Rotary Charcoal recovery ratio (%)
Dried Bark	0	45.1	79
Dried Sawdust	0	30.3	65
Green Sawdust	118	28.6	69
Dried Woodchips	0	29.5	73
Dried Planer Shavings	0	30.6	71
Dried Dockings-shredded	0	29.1	74

CONCLUSIONS

Laboratory carbonisation trials on *P. radiata* residues in the form of green sawdust, green woodchips, green bark, dry planer shavings and shredded dockings successfully produced charcoal. The fluid bed method of carbonisation using air fluidisation produced good yields of charcoal in both coarse and fine sizes. These were in the range 65 - 79% of the idealised yields of charcoal as produced by pyrolysis of oven dried wood in the absence of oxygen. The fluid bed carbonisation enables the volatile by-products of carbonisation to be burnt during the carbonising process. Heat energy can be recovered from the combustion of volatiles. Carbonisation times in the fluidised bed are extremely short as compared to that for conventional pyrolysis because of the excellent heat transfer between the gas, wood, charcoal and bed material within the fluidised bed.

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FATIGUE AND CREEP IN WOOD BASED PANEL PRODUCTS: AN INTRODUCTION TO RESEARCH AT THE UNIVERSITY OF BATH

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ABSTRACT

The fatigue performance in bending of representative wood based panel products has been investigated. The research primarily evaluated the effect of loading frequency on the fatigue life of flooring grade chipboard and the fatigue performance of oriented strand board (OSB) and medium density fibre board (MDF). Design parameters for flooring are based on deflection and duration of load. However, panel products used for flooring may be subjected to fatigue loading such as vibrating machinery, fork lift truck motion and pedestrian motion.

Parallel fatigue and creep tests were performed simultaneously at the same peak stress. This enabled the results of cyclic and creep loading to be compared. Stress versus strain hysteresis loop capture was used as a non-interruptive method to evaluate fatigue damage in the materials. The effects of the level of stress applied and of changing the loading frequency upon the damage accumulation in OSB, chipboard and MDF is shown using the hysteresis loop parameters.

The fatigue life of chipboard reduced when the frequency of fatigue loading was reduced. The changes in the hysteresis loop area between the first and the last loop capture suggest that OSB, chipboard and MDF all have fatigue limits slightly below the 20% stress level. The fatigue limit for MDF lies slightly below those for OSB and chipboard but there was no correlation with the constituent particle size. The fatigue performance of the three panel products normalised by the static strength reduced as follows: chipboard>OSB>MDF. When compared with respect to the applied stress, however, the fatigue performances reduced as follows MDF>OSB>chipboard representing the relative bending strengths.

INTRODUCTION

Wood based panel products are widely used for many applications including flooring, roof decking, packaging and furniture. Panel products used as flooring can be exposed to a combination of creep and fatigue loading throughout their lifetime. Creep loads are produced by static masses, such as heavy machinery or furniture standing on a floor, and fatigue loads arise from intermittent loads, such as fork lift trucks or people in motion, or from vibrating machinery. Fatigue and creep loading both produce failure in a material at a stress below the breaking stress of that material. Failure may mean a catastrophic fracture in fatigue, or as is generally the case for creep loading, deformation of the material to such an extent that it is unacceptable for the purpose it is being used.

The use of panel products in load bearing applications is limited by their creep performance because they are viscoelastic and continue to deflect with time when subjected to a constant load. The UK's Building Research Establishment (BRE) has conducted extensive research on quantifying and predicting the creep behaviour of wood based panel products for over twenty years. Flooring in domestic and industrial buildings is exposed to fatigue as well as creep loading and this is widely ignored. However, at BRE[1,2] slow cyclic fatigue (on-off loading) of chipboard has also been evaluated.

The work at Bath University[3-7] began in 1990 and extends the work at BRE[2,8,9] by examining the cyclic (fatigue) loading of panel products. The initial research[1,3,6] produced a constant life diagram and a set of S-N (stress versus number of loading cycles to failure) diagrams for a flooring grade chipboard. The constant life diagram and S-N plots allow the fatigue life to be predicted under a range of fatigue loading regimes. In the on going research at Bath a more comprehensive constant life diagram will be produced for MDF.

The majority of the work to date has examined the response of three selected panel products to fatigue and creep loading, in order to simulate the loading of factory floors. Creep and fatigue tests were performed on chipboard, OSB and MDF. The fatigue testing of chipboard was carried out at three frequencies determined by the rate of application of stress[5,7] to determine the effect of loading frequency on fatigue life. The fatigue life of elastic materials is independent of the loading frequency but for viscoelastic materials such as chipboard this is not the case. If the effect of the loading frequency is not determined the material may be over designed for its purpose, or under designed leading to failure in service. The testing of OSB and MDF was only performed at the medium frequency and the relative fatigue performances of the different panel products were evaluated. OSB and MDF are continually finding new applications some of which will receive fatigue loading. In the UK OSB is used for domestic flooring and MDF is used for stair treads both of which receive fatigue loading. The evaluation included an attempt to correlate the properties to the relative size of the constituent wood particles denoted as large, medium and small. The exact particle dimensions were not important. OSB is composed of long wood flakes (large), chipboard has smaller chips (medium) and MDF is made up of fibres and fibre bundles (small).

During all the tests[1,4-7], stress versus strain hysteresis loop capture was used as a non-interruptive method to assess damage accumulation due to fatigue loading. The loops were analysed to give the energy dissipated per cycle, the changes in the dynamic and fatigue moduli, and underlying creep deflections.

MATERIALS AND METHODS

Three types of wood based panels were tested. 1) A three layered structural grade C4 **chipboard,** manufactured in accordance with BS 5669: Part 2: 1989, consisting of softwood particles of spruce and/or fir bonded with an MUF resin. 2) A moisture-resistant**OSB,** grade F2, also three layered, manufactured in accordance with BS 5669: Part 3: 1992, composed of soft wood particles, in this case scots pine bonded with about 2.5 weight percent of PF resin. 3) A moisture-resistant MDF manufactured in accordance with BS 1142: Part 2: 1989. Again this was a softwood board composed from fibres and fibre bundles of sitka spruce and pine bonded with 6-8 weight percent of PF resin.

BRE provided conditioned side-matched sets of four samples of: chipboard, OSB and MDF, all 50 mm wide by 330 mm long. The chipboard and MDF samples provided were 18 mm thick and the OSB samples were 19 mm thick. Side-matched sets of four samples were employed to minimise the effect that the inherent variability of the materials would have upon the scatter of the fatigue data collected.

Initially the two outside samples of each side-matched set were tested to determine the mean bending strength (BS) for the set. The left inner sample was loaded sinusoidally in fatigue at

R=0.1 where: $R = \frac{\text{minimum stress}}{\text{maximum stress}}$

this is referred to as non-reversed loading, ie. the stress on the sample is always positive. Loading at R=0.1 produces a relatively low mean stress, with a large cyclic stress range[5], and the maximum/peak applied stress is ten times greater than the minimum applied stress. The right inner sample was loaded in creep at the same peak stress level. All the samples, of all three materials, were conditioned and stored at 20°C ± 2°C and ~65% RH.

All the tests in fatigue, creep and static loading were performed using the equipment shown in figure 1. All loads were applied in four point bending in accordance with BS 5669: Part 1: 1989 with a span to depth ratio of 16:1 in quarter point loading with the distance between the outer supports fixed at 300 mm.

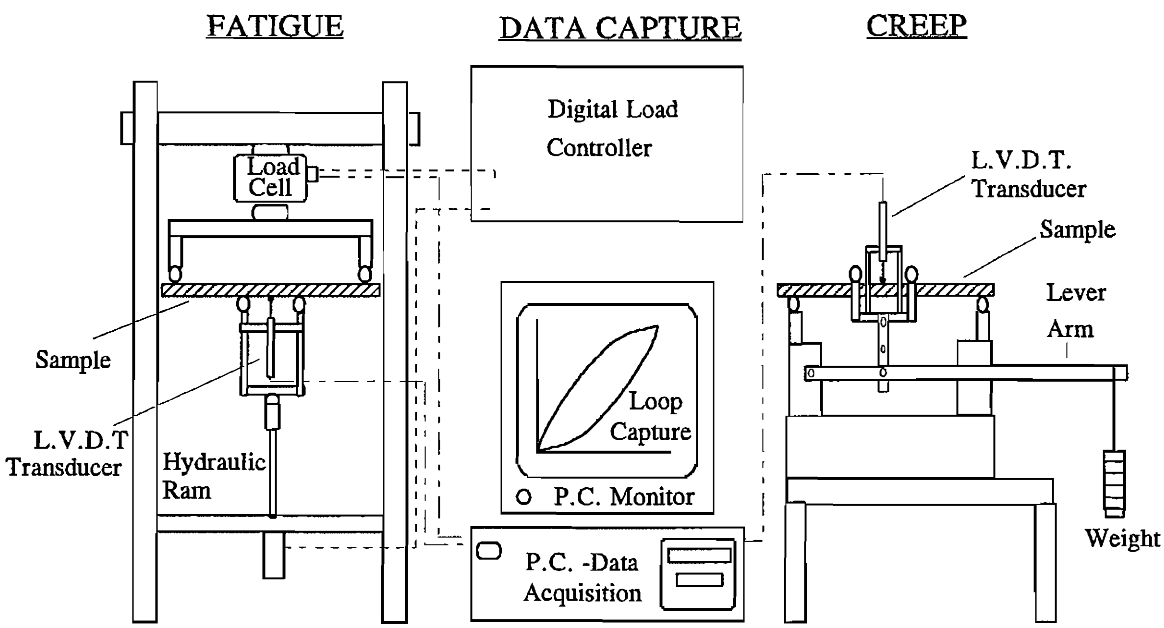


Fig. 1 Diagram of the parallel fatigue and creep, testing equipment.

The short term static tests, and the fatigue tests, were all performed on a Dartec 5 kN servo-hydraulic fatigue machine operating under load control. The later work[4,5,7] used a Dartec M9500 digital controller operating on a feedback loop. The creep testing was performed simultaneously in parallel with the fatigue testing using a creep rig provided by BRE. The loads were applied to the creep samples via a lever arm and pivot arrangement with the same roller configuration as for the fatigue tests. The true centre point deflection of the matched creep and fatigue samples were measured throughout all tests using linear variable differential transformer (LVDT) displacement transducers. These deflections and the load measurements were captured and manipulated by a custom made computerised fatigue data acquisition system (FDAS) to produce stress versus strain hysteresis loops.

The fatigue tests on chipboard were performed at three frequency ranges determined by the loading rates of 1.2 MPa/s, 12 MPa/s and 150 MPa/s. The implementation of these loading rates in fatigue testing produced test frequencies increasing by an order of magnitude each time, resulting in low frequencies (0.015-0.15 Hz), medium frequencies (0.15-3.0 Hz) and high frequencies (3.0-15.0 Hz)[5,7]. The aim was to determine the effect of frequency on the fatigue performance of chipboard and to compare its performance in fatigue and creep.

OSB and MDF were both tested at the medium frequency only. The objective was to compare the fatigue performances of these two materials with that of chipboard and if appropriate to relate the findings to the difference in particle size between the materials.

The mean BS of the outside two samples was taken as the 100% stress level and was used to calculate the percentage stress levels to set up the fatigue and creep tests. Chipboard samples were tested at all three test frequencies at stress levels of 80, 70, 60, 50, 40, 30 and 20% of the mean BS of the outside two samples. Medium frequency testing of OSB and MDF was also performed at 80, 70, 60, 50, 40, 30 and 20% stress levels.

The parallel fatigue and creep tests of side-matched samples were started almost simultaneously. In each test the fatigue sample was sinusoidally cycled up to the percentage of the mean BS (peak stress level) while the creep sample was constantly loaded at that peak stress level. The cycle counter on the load controller was stopped when a fatigue sample failed, recording the number of cycles to failure. If the fatigue sample had not failed after 10^5 loading cycles for low frequency loading, 10^6 cycles for medium frequency loading and 10^7 cycles for high frequency loading, then it was considered to be a runout and testing was stopped. This allowed samples to fail at the 50% stress level for each frequency. Runout samples were then statically tested to failure to determine their residual bending strengths[5]. All of the static tests were performed at the loading rate used in the respective fatigue tests.

Stress versus Strain Hysteresis Loop Capture

The quantification of damage is difficult to achieve by either non-destructive or non-interruptive processes. Stress versus strain hysteresis loop capture during fatigue testing, however, is a method that enables quantitative measurements of damage accumulation to be continuously made without the need to stop the test. When a load is applied to any material that does not respond in a perfectly elastic manner there is a lag between the load/stress being applied and the strain produced in the material. Wood and wood based materials are viscoelastic, so the lag between the applied stress and the resulting strain produces hysteresis. The lag is caused by internal friction and the accumulation of fatigue damage, represented as a dissipation of energy in the sample.

During testing the applied loads and the true centre point deflections from both samples were monitored by the FDAS and were entered into standard beam equations to calculate the surface stresses and strains. When a full loading and unloading fatigue cycle has taken place then a loop is produced and can be plotted as stress versus strain. These hysteresis loops were captured and printed at pre-determined time intervals. Analysis of the hysteresis loops produced during consecutive loading and unloading allows changes in the energy dissipated per cycle (hysteresis loop area), dynamic moduli (average stiffness), fatigue moduli and the underlying creep effects following fatigue loading, to be determined[3].

Results and Discussion

An extensive evaluation of the **strength variability** within the different board types and of the effect of loading rate on the strength of chipboard was performed[5]. When the materials were loaded at the same rate of application of stress, the **mean bending strengths** were: 47.9 MPa for MDF, 27.9 MPa for OSB and 21.0 MPa for chipboard. The strength variability for OSB was considerably greater than for chipboard and MDF. This affected the analysis of the results for OSB and they did not correlate as well as the other results.

The effect of **loading frequency** on the fatigue performance of chipboard is demonstrated in figure 2. Least squares linear regression lines have been fitted to the fatigue data for the three loading frequencies. In figures 2 and 3, -0.6 on the $\log_{(10)}$scale is a quarter of a loading cycle representing ramp loading to failure. The number of loading cycles to produce fatigue failure in chipboard falls as the loading frequency is reduced from high to medium, and from medium to low[5,7]. The magnitude of the reduction decreases as the stress level is reduced from 80% of the bending strength down to 20%. The effect of loading frequency has serious implications if the fatigue performance of chipboard was implemented in design codes. In materials that are elastic, loading frequency has no effect on the fatigue life of the material. In the case of chipboard, high frequency testing could only be used to determine the fatigue life for design if a scaling parameter was included to account for the loading frequency.

The **fatigue performances of OSB, chipboard and MDF** have been compared with the fatigue data normalised using the materials bending strengths[5] and based on the raw applied stress data[4,5]. Figure 3 shows the fatigue performances normalised by the bending strengths. Least squares linear regression lines are fitted to the data for each material. The plot demonstrates that, based on normalised data, for the representative materials tested the fatigue performance of the chipboard was superior to the OSB which was superior to the MDF. This did not correlate to the constituent particle size. Normalised stresses are generally used in evaluating the long term performance of panel product to allow the performance of products of widely different strengths to be compared. When the materials were compared **based on the applied stress**[4,5] (MPa) then the relative fatigue performances were reversed. The performance of the MDF was superior to the OSB, which was superior to the chipboard. These results represent the relative strengths of the three materials. Again this did not correlate to the constituent particle size. The S-N lines converged as the number of loading cycles was increased so the fatigue performances of the three materials would be similar when the stresses applied are low. Although the MDF tested was considerably stronger than the OSB and chipboard tested, it is the creep performance of MDF that will restrict its use in structural applications. The propensity to creep for wood based panels increases as the constituent particle size is decreased[9].

Stress versus strain hysteresis loop capture proved to be an excellent technique for following fatigue damage in the materials without interrupting the fatigue tests[3-7]. The parameters obtained using the FDAS were: the surface microstrain and stress for the creep sample, and for the fatigue sample were the maximum and minimum surface microstrains and stresses, the dynamic modulus, the fatigue modulus and the hysteresis loop area. These parameters are extensively evaluated in the references cited[1,4-7] and all proved useful in assessing the damage to samples loaded in fatigue and in creep.

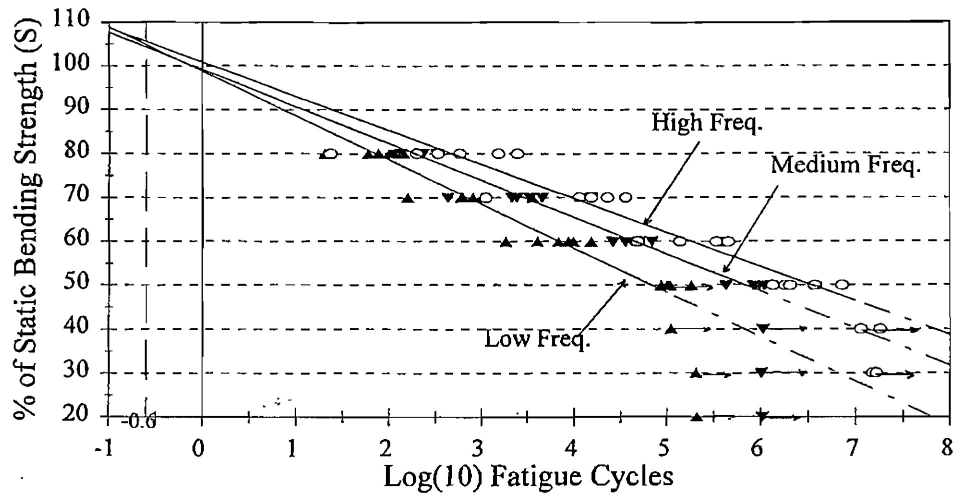
The hysteresis loop area proved particularly useful in predicting fatigue limits for the three materials tested. A fatigue limit occurs for some materials and is a level of applied stress where the material can be subjected to an infinite number of fatigue loading cycles and failure will never occur. The changes in the hysteresis loop area, shown by the difference between the initial and final loop areas are shown in figure 4 for OSB and chipboard, and in figure 5 for MDF. The change in the hysteresis loop areas for all three materials decreased with reducing stress level tending towards zero. The hysteresis loop area does not change as a result of fatigue loading at the lowest stress level indicating that no damage is being produced and hence the material will not fail[5,7]. This suggests that both chipboard and OSB have a fatigue limit at just below 20% of the bending strength and this occurs at just below 15% of the bending strength for MDF. The fatigue limit for chipboard was unaffected by the frequency of loading. The existence of these fatigue limits was supported by the other hysteresis loop parameters, the fatigue lives of the samples tested and the residual strengths[5,7].

Fig. 2

S-N PLOT FOR CHIPBOARD IN 4pt. BENDING

R=0.1, LOW, MEDIUM & HIGH FREQUENCIES

(Static data and runout data were excluded from the regression analysis)



▲ Low Freq. Log(N)=-0.099(S)+9.79 ▼ Medium Freq. Log(N)=-0.119(S)+11.76

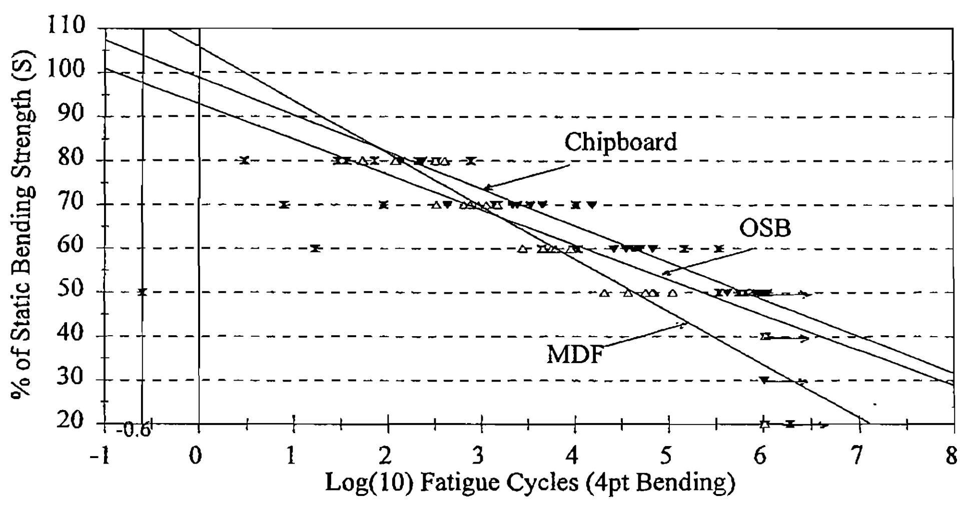
○ High Freq. Log(N)=-0.129(S)+12.98

Fig. 3

S-N PLOT FOR CHIPBOARD, OSB AND MDF

R=0.1, AT MEDIUM FREQUENCY

(Static data and runout data excluded from the regression analysis)



▼ Chipboard Log(N)=-0.119(S)+11.76 x OSB Log(N)=-0.125(S)+11.62

△ MDF Log(N)=-0.083(S)+8.79

Fig. 4

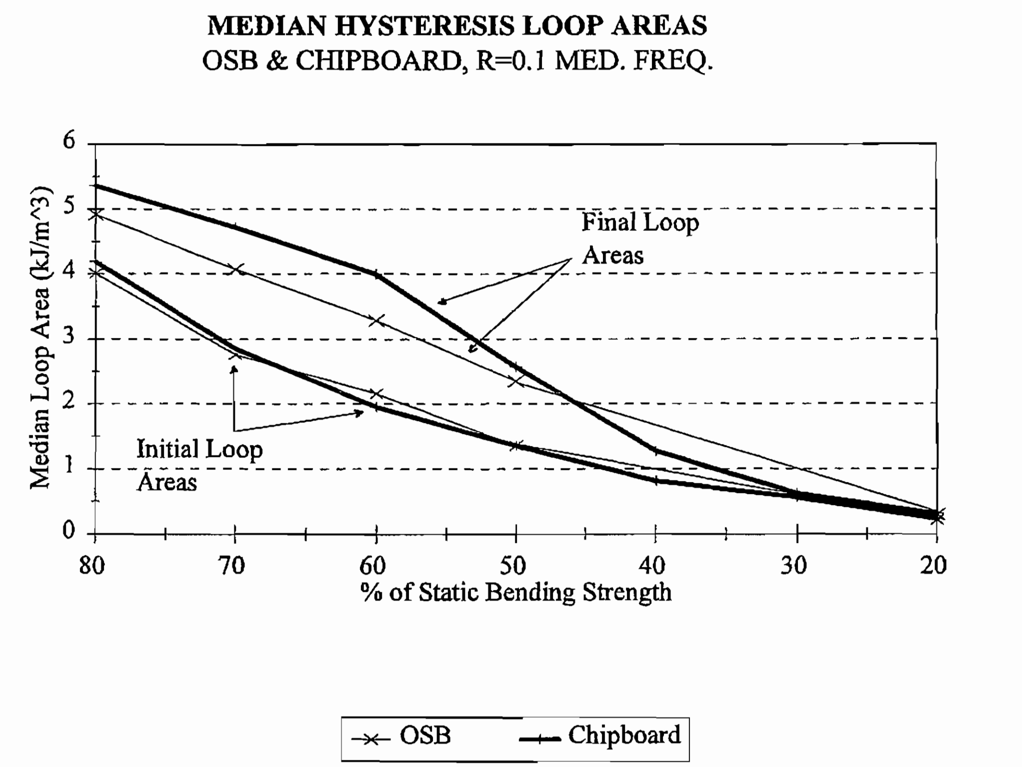
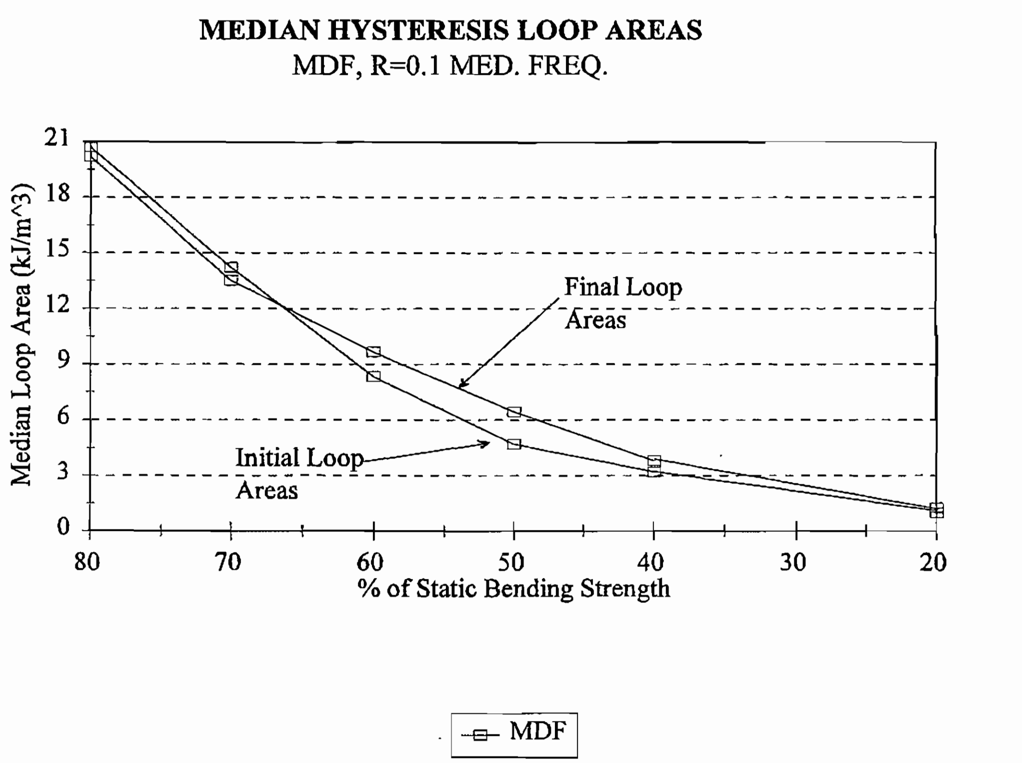

MEDIAN HYSTERESIS LOOP AREAS
OSB & CHIPBOARD, R=0.1 MED. FREQ.
Median Loop Area (kJ/m^3)
6
5
4
3
2
1
0
80
70
60
50
40
30
20
% of Static Bending Strength
Final Loop Areas
Initial Loop Areas
OSB
Chipboard

Fig. 5


MEDIAN HYSTERESIS LOOP AREAS
MDF, R=0.1 MED. FREQ.
Median Loop Area (kJ/m^3)
21
18
15
12
9
6
3
0
80
70
60
50
40
30
20
% of Static Bending Strength
Final Loop Areas
Initial Loop Areas
MDF

Conclusions

This collaborative research has helped to bridge the gap between the existing knowledge of creep in wood based panels and the extremely limited knowledge of the fatigue performance of these panels. It has been shown that the fatigue life of chipboard reduces as the loading frequency is reduced. When normalised by the bending strength, the relative fatigue performances of the three materials were: chipboard>OSB>MDF. This was reversed if the applied stresses are considered with MDF>OSB>chipboard and neither correlated to the size of the constituent wood particles. All three materials were shown to have fatigue limits. This occurred just below the 20% stress level for OSB and chipboard, and at just below the 15% stress level for MDF. The fatigue limit for chipboard was unaffected by the loading frequency.

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NONDESTRUCTIVE EVALUATION OF RECONSTITUTED WOOD BASED PANELS*

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ABSTRACT

Nondestructive resonance, and static bending tests were carried out on reconstituted wood panels, 100 mm x 350 mm, according to Australian Standard (AS/NZS4266.0: 1995). Nondestructive tests were based on impact induced flexural vibrations, and the elastic constants were calculated following spectral resonant frequency analysis.

The repeatability of individual dynamic measurements was extremely good, and as expected, the coefficients of variation of nondestructive tests and static tests were very similar. The nondestructive dynamic MOE corrected for shear and rotary inertia effects, was positively correlated with MOE and MOR from static tests, but the uncorrected MOE showed a better correlation. Lamination of MDF with hardwood veneer increased both dynamic and static MOE, and MOR by 30% and 14% respectively, but unexpectedly in particleboard, the increases were over 60% and over 120% respectively. This study confirmed that nondestructive evaluation using dynamic resonant testing is eminently suitable for studying properties of reconstituted board products.

INTRODUCTION

The increasing use of reconstituted wood based panels in furniture manufacture requires sound knowledge of the properties and long-term performance of these materials. For this reason, a study has been undertaken on the applicability of nondestructive dynamic testing for the assessment of modulus of elasticity (MOE) and modulus of rupture (MOR) of laminated furniture panels.

Typical furniture panels are made from three layer composite board: the core, being particleboard, fibreboard or plywood, and this is laminated with a thin layer of decorative veneer, melamine laminate or other laminating material. Existing standards relating to wood-based panels specify testing methods and requirements for various grades of particleboard and fibreboard. Stiffness and strength criteria are defined only for unlaminated boards. Limited data are available for the furniture designers and manufacturers on the mechanical properties of laminated furniture panels.

A major requirement for furniture panels is good long-term performance in various climatic conditions. Performance evaluation involves the assessment of MOE and strength properties in extremes of relative humidity and temperature which can occur in service.

To determine the changes of panel properties under various conditions, a large number of matched samples is required for destructive strength testing. However, the use of nondestructive testing enables the assessment of changes of panel properties as they occur on the same samples. It would not only reduce the number of samples, but would also eliminate the error caused by within sheet variation of properties. Furthermore nondestructive testing

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has great value in assessing actual furniture panels in both stable and changing environmental conditions. The main aims of this paper are to present an assessment of the suitability of resonance testing as one form of nondestructive testing for the determination of elastic properties of reconstituted wood products.

MATERIALS AND METHODS

Test material used included 10-12 samples of each of 3, 5, 7 and 9 ply plywood, LVL, standard and moisture resistant (MR) particleboard, and medium density fibreboard (MDF); both with and without melamine and wood veneer lamination. The wood veneer used was 0.4mm, *Eucalyptus regnans* F.Muell. (mountain ash). The samples were cut from sheets purchased from a local supplier which are typical of material produced for the furniture and joinery industry in Australia.

Static bending tests were carried out on specimens, 100 mm x 350 mm, according to Australian Standard (AS/NZS4266.0: 1995) to determine static strength and MOE. Nondestructive tests were carried out using impact induced flexural vibrations and the elastic constants were calculated from the spectral analysis.

Figure 1. Typical nondestructive test setup

In the nondestructive test, samples were impacted on their faces with a light hammer to induce flexural vibrations. A small microphone, type SONY, ECM-T140, was used to detect the audible vibrations. A typical experimental setup is shown in Fig. 1. A system was developed for capturing transient data and the subsequent determination of spectral components. Test samples were suspended from flexible supports on edge from their theoretical nodal points (0.224 of the length from each end) as shown in Fig. 1.

The vibration detection system consisted of a transient recorder module configured using an external variable gain wide bandwidth preamplifier with a PCL1800 analogue to digital (A/D) board and DASYLAB software, written by DASYTECH, Germany. The preamplifier gain was adjusted so as to produce voltage outputs swinging in the range -5 V to +5 V from transients generated by impacts to the test specimens. The input stage of the recorder was set to respond to a narrow range of input levels to ensure that only repeatable impacts were recorded and processed. Each transient was saved as a file and processed at a later stage. A simple spectrum analyser was implemented in the transient recorder module to provide an indication of the resonance peaks immediately after the test was performed. A 50 kHz sampling was used for all the tests producing a frequency resolution of 2.9 Hz. The spectrum analyser module was also configured with DASYLAB. This module was programmed to read the file containing the transient signal, and perform a fast Fourier transform (FFT) and generate output files containing spectral data. The final step in the analysis was carried out using PEAKFIND, a program specifically developed to identify peak frequencies and use them to calculate the elastic moduli. The dynamic flexural modulus E, and the dynamic shear modulus, G, after applying the "Timoshenko correction" for rotary inertia and shear were calculated according to Hearmon (1958). Only the fundamental and the first overtone were used in the calculations. All the results were confirmed by application of an alternate procedure developed by Chui (1991).

RESULTS AND DISCUSSION

Spectral analysis and calculation of elastic moduli

Spectral peaks were clearly identifiable as single peaks corresponding to the fundamental and first overtone in almost all the panels. However, the interpretation and selection of spectral peaks of some 7 ply specimens and one 9 ply sample with parallel face veneer were sometimes complicated by the occurrence of multiple peaks near the first overtone. A careful inspection was made of the panels, but no clear picture of the reasons for the production of multiple peaks could be ascertained. It is suggested that a likely cause of additional peaks is a critical interaction between sample dimensions and the cross banding of the plywood, which may have introduced additional modes of vibration of the panel acting as a plate. Normally, modal analysis would be needed to resolve these difficulties, but in this experiment, facilities were not available for modal detection; the choice of the correct peak was made on the basis of its magnitude and by comparison with results from calculations from the higher overtones.

Nondestructive Properties

A complete summary of results is presented in Table 1. Generally the values of elastic moduli correspond well with mean values expected for the particular panel type. The corrected MOE values of all products were approximately 8% higher than the uncorrected (Euler) ones. However, for plywood with parallel face veneer the correction was 17%.

Table 1 Summary of mean results of all samples comparing dynamic MOE (DynMOE) with static MOE and other characteristics. (Values in *brackets* represent the coefficient of variation (%)). Veneer with parallel and perpendicular faces indicate grain direction of face veneers in relation to the bending direction.

	DynMOE uncorrected (GPa)	**DynMOE corrected (GPa)**	**MOE static (GPa)**	**MOR (MPa)**	**Density (Kg/m^3)**
5 ply (parallel faces)	11.27	13.14	8.83	58.88	640
	(4.2)	(6.4)	(6.1)	(13.2)	(4.1)
5 ply (perpendicular	3.6	3.85	3.0	32.85	650
faces)	(11.5)	(12.6)	(10.8)	(15.4)	(2.0)
7 ply (parallel faces)	9.65	11.04	7.0	53.13	700
	(20.9)	(14.4)	(20.3)	(22.8)	(3.7)

7 ply (perpendicular faces)	5.00 (5.5)	5.42 (7.0)	4.13 (6.4)	42.13 (5.7)	705 (4.1)
9 ply (parallel faces)	14.91 (7.4)	17.76 (6.8)	12.24 (12.1)	74.43 (13.7)	755 (1.5)
LVL	14.06 (7.1)	15.24 (5.7)	14.49 (7.1)	69.56 (5.0)	670 (4.2)
MDF	4.76 (3.2)	5.13 (3.6)	3.84 (2.8)	39.10 (2.7)	705 (1.2)
MDF MR	4.59 (1.0)	4.95 (1.3)	3.64 (3.4)	39.00 (4.7)	720 (0.5)
MDF MR + melamine	5.04 (2.4)	5.4 (1.3)	4.04 (5.7)	38.43 (3.5)	750 (1.1)
MDF MR + veneer (parallel faces)	6.18 (2.1)	6.85 (2.6)	4.88 (2.2)	44.5 (3.9)	740 (4.9)
Particleboard	3.94 (6.2)	4.18 (4.0)	2.92 (8.1)	15.49 (9.2)	715 (2.6)
Particleboard + melamine	4.64 (6.2)	5.01 (6.8)	3.57 (7.2)	19.85 (10.3)	705 (2.5)
Particleboard MR + veneer (parallel faces)	6.24 (7.0)	6.89 (6.9)	4.87 (6.8)	34.43 (12.3)	690 (2.4)
Particleboard MR	4.14 (4.5)	4.40 (5.0)	3.18 (6.3)	18.71 (6.2)	675 (2.2)
Particleboard MR + melamine	4.50 (5.1)	4.81 (5.2)	3.53 (7.2)	19.21 (6.2)	690 (2.9)
Particleboard MR + veneer (parallel faces)	6.64 (2.8)	7.28 (2.8)	5.23 (3.6)	43.66 (5.4)	700 (3.0)

Comparing the uncorrected dynamic MOE and the static MOE measured from static bending tests, in this experiment, the dynamic values were approximately 25-38% higher than the static ones. Although it is well known that the dynamic MOE is usually about 5-8% greater than the static value for solid wood (Kollman and Krech 1960), limited data are available for reconstituted products from resonance studies. Pellerin and Morschauser (1974) obtained values about 14% greater for particleboard, but this was for stress wave velocity^2, which is proportional to MOE. Shyamasunder *et al.* (1994) obtained increases of 22% for Oregon 5 ply. Using stress waves Tang and Schroeder (1994) obtained average increases of 27% for southern pine LVL, and Bozhang and Zhiyong (1994) obtained increases of 5.2% for large sheets of particleboard. It may be expected that the dynamic MOE should be higher than the static value as products such as MDF and particleboard are likely to have a reduced linear elastic region. The Instron stress-strain plots show that property clearly.

Inspection of Table 1 shows that for plywood and LVL, the range of the coefficient of variation of both MOE and MOR is between 5-23%, while for MDF, the variation is under

6%. MOR varied between 5-12%, and MOE varied between 3-8% for particleboard. The density variation of all products was well under 5%.

Plywood products exhibited the largest variation in MOE and MOR between samples, being in excess of 20%, for static and dynamic values. On the other hand, the variation in elastic properties between samples for MDF was under 5%, while that for particleboard was approximately 10%. It should be noted how consistent the coefficients of variation were between the dynamic and static tests (Fig. 2). This characteristic was seen to be critical for the successful application of nondestructive testing.

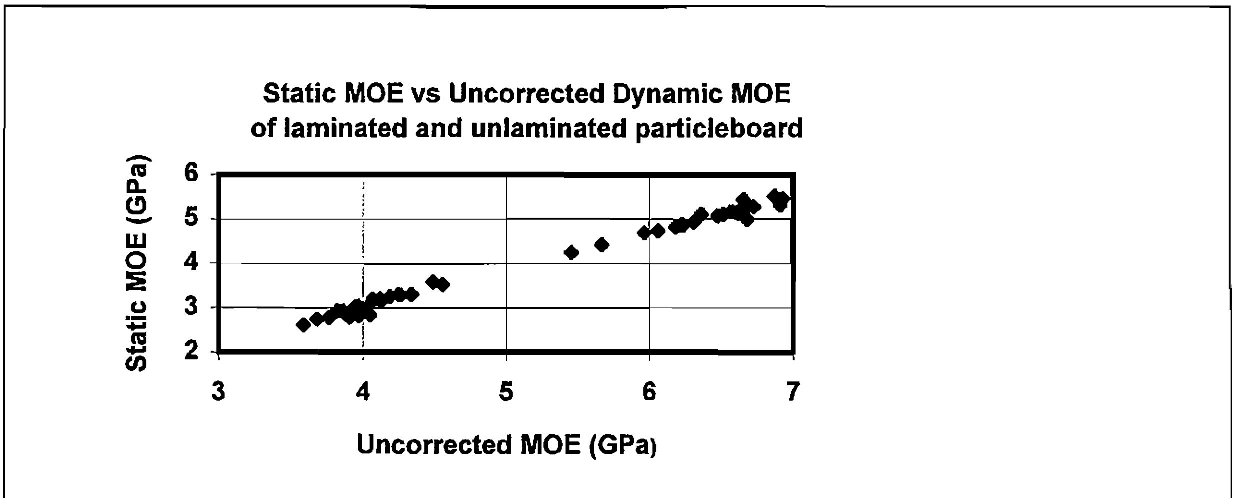

Figure 2 Typical relationship between static MOE and uncorrected dynamic MOE of unlaminated and wood veneered particleboard (includes moisture resistant and standard panels). Dynamic MOE values of unveneered panels are between 3.5 and 4.6 GPa.

Upon further inspection of Table 1, it can be seen that for unlaminated and veneer laminated MDF, stiffness increased about 30%, but strength increased only 14%, while for particleboard, the stiffness increased over 60%, and the strength increase was over 120%, for the same type of hardwood veneer. Biblis *et al.* (1996) also obtained increases of over 96% in MOE and over 117% in MOR for oriented strand board panels laminated with southern pine veneer. In the case of MDF, it may be expected that increasing surface stiffness is less likely to improve strength markedly because the mode of failure, in our experiments was almost always in shear. However, for particleboard, there was a greater increase in stiffness, and a marked increase in strength. A substantial increase in strength may be expected for particleboard as the mode of failure is not in shear, but in tension. This marked increase in strength of particleboard could be of considerable practical significance as it would appear to be possible to construct panels of relatively high strength by laminating low strength particleboard with veneer. Consequently thinner panels could be constructed for the same stiffness and strength which may be useful for more visually appealing industrial shelving and flooring.

One of the main objectives of the experiments was to determine the suitability of nondestructive testing for assessing the elastic constants on the same sample. An examination of Table 2 shows clearly that the nondestructive assessment of MOE is highly correlated with uncorrected dynamic MOE for all products except for the 9 ply samples. Shyamasunder, *et al.* (1994) obtained comparable correlations for Oregon plywood, and

Bozhang and Zhiyong (1994) obtained even higher correlation (r = 0.990) for full size particleboard panels, Ross (1984), and Ross and Pellerin (1988) obtained similarly high correlations in their tests on particleboard (r = 0.96-0.97) On the other hand, Dunlop (1980) obtained much lower correlations with MOE for commercial particleboard using longitudinal stress wave velocity^2 (r = 0.52-0.65), and even lower values for MOR, (r = 0.11-0.54).

In most cases in this experiment, over 90% of the variation in the static MOE is explained on the basis of the uncorrected dynamic MOE. Evidently the correlation for standard and moisture resistant MDF was lower compared to the same laminated material and other products. Ross and Pellerin (1994) cite that Vogt (1984) also obtained somewhat lower correlations (r = 0.72) for MDF using longitudinal stress waves. In this case the correlations with corrected dynamic MOE were only marginally better. The lower correlation is difficult to account for at this stage and will require further study. In addition, the correlations between static MOE and corrected dynamic MOE of 9 ply and LVL were considerably lower than the uncorrected values. In both cases the samples were longer than the standard specimens to compensate for the increased thickness, and the specimens were tested in a 3 point bending mode without shear correction.

Table 2 Correlation coefficients relating nondestructive MOE variables and static MOE. Veneer with parallel and perpendicular faces indicate grain direction of face veneers relative to the bending direction.

	Correlation coefficient⁺	
	Uncorrected dynamic MOE	Corrected dynamic MOE
5 ply (parallel faces)	0.810	0.768
5 ply (perpendicular faces)	0.990	0.977
7 ply (parallel faces)	0.958	0.988
7 ply (perpendicular faces)	0.943	0.966
9 ply (parallel faces)	0.857	0.381
LVL	0.793	0.533
MDF	0.660	0.697
MDF MR	0.592	0.705
MDF MR + melamine	0.977	0.896
MDF MR + veneer (parallel faces)	0.954	0.874
Particleboard	0.928	0.723
Particleboard + mealmine	0.973	0.955
Particleboard + veneer (parallel faces)	0.995	0.977
Particleboard MR	0.902	0.869
Particleboard MR + melamine	0.968	0.945
Particleboard MR + veneer (parallel faces)	0.870	0.818
TOTAL	0.887	0.817

The correlation between MOR with nondestructive properties and static MOE are shown in Table 3. Taking the products individually, for predicting plywood strength, correlations involving 5 ply with parallel faces were poor compared to those for 7 ply, most likely because of the presence of knots in face veneers, whereas the correlations for panels with perpendicular face veneers, relatively clear of knots, were good for both 5 and 7 ply samples.

⁺ Correlation coefficients > 0.558 are significant at least at the 5% level

The correlations for 9 ply were poor, but also there was no correlation between static MOE and strength. The correlations for LVL were poor as well. Similarly the correlations for moisture resistant melamine laminated MDF were negative and low. Statistical analysis indicated that these correlations were not significant, consequently it was concluded that no correlation was evident. While the correlations between dynamic MOE and static MOE were high in all cases for both MDF and particleboard laminated with wood veneer, the correlations with strength were low or not evident.

Table 3 Correlation coefficients relating nondestructive and static MOE and damping with MOR. Veneer with parallel and perpendicular faces indicate grain direction of face veneers relative to the bending direction.

	Correlation Coefficient+	
	uncorr. dyn. MOE	static MOE
5 ply (parallel faces)	0.306	0.581
5 ply (perpendicular faces)	0.974	0.952
7 ply (parallel faces)	0.911	0.967
7 ply (perpendicular faces)	0.798	0.777
9 ply (parallel faces)	0.223	0.008
LVL	- 0.174	0.004
MDF	0.441	0.857
MDF MR	0.612	0.910
MDF MR + melamine	- 0.261	- 0.340
MDF MR + veneer (parallel faces)	0.470	0.560
Particleboard	0.816	0.636
Particleboard + mealmine	0.915	0.847
Particleboard + veneer (parallel faces)	0.311	0.245
Particleboard MR	0.809	0.932
Particleboard MR + melamine	0.372	0.370
Particleboard MR + veneer (parallel faces)	0.543	0.674

It can be suggested that while lamination of reconstituted materials improves stiffness, this improvement may not produce an equivalent increase in strength. Dunlop (1980) in his study on particleboard obtained results which showed that the stiffness of particleboard panels, indicated by the square of the longitudinal stress wave velocity, were influenced greatly by the surface layers. His correlations with MOR were also low, but they were shown to improve with greater surface to core uniformity. In these studies no attempt was made to combine other measured characteristics to improve strength prediction. This will be attempted in future studies.

CONCLUSION

Nondestructive resonance testing using transverse vibrations proved suitable for the determination of MOE in reconstituted panels. A high correlation exists between dynamic and static MOE for all reconstituted products. The correlations of nondestructive MOE with MOR are generally satisfactory, except for MDF and in some cases for plywood. Particleboard increases in strength by over 120% when veneered, in contrast to MDF which

+ Correlation coefficients > 0.558 are significant at least at the 5% level shows only a 14% increase. Lower correlations are obtained between dynamic MOE and strength for veneered compared to unveneered panels.

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DYNAMIC MECHANICAL THERMAL ANALYSIS OF WOOD-BASED PANEL PRODUCTS

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ABSTRACT

Dynamic Mechanical Thermal Analysis (DMTA) of skin and core samples of chipboard, oriented strand board (OSB) and medium density fibreboard (MDF) over the temperature range 25 to 200°C indicated the differences in elastic modulus between the skin and core layers of the three panels. This can be related to the densification of the wood particles and varying resin distribution within each panel product. Elastic moduli decreased with increasing temperature for all three panels. Skin layers exhibited higher elastic moduli compared with core layers. Tan delta values increased with temperature. Lower resin levels in OSB compared with MDF and chipboard could account for less marked differences observed between the elastic moduli for the skin and core layers for this panel. Trends in increases in loop areas observed during fatigue testing correlated with increasing tan delta results from the DMTA testing. MDF and chipboard exhibited greater loop areas than OSB and a larger decrease in tan delta during testing than OSB.

1. INTRODUCTION

The technique of Dynamic Mechanical Thermal Analysis (DMTA) has been utilised to study skin and core sections of medium density fibreboard, (MDF), chipboard and oriented strand board (OSB). The results of this investigation have been compared with the fatigue and creep performance of the three wood-based panel products loaded at equivalent absolute stress levels (Pritchard et al, 1996), based on work by Thompson (1996a).

Chipboard, OSB and MDF are viscoelastic materials. At low levels of applied stress they can be considered to behave as elastic materials. This is not the case for real applications where time becomes an important variable (Dinwoodie, 1989). They behave neither as true elastic solids or true viscous solids but somewhere in between, thus a treatment of their mechanical response to load should be based on viscoelastic models.

Applying a sinusoidal stress to a perfectly elastic solid will result in the stress and strain deformations occurring exactly in phase. If the material is perfectly viscous then the strain deformation will lag 90° behind the applied stress. When the sinusoidal stress is applied to a viscoelastic material the resultant strain lags behind the applied stress by some phase angle δ, where $\delta<90°$. This angle is referred to as the loss angle (delta) and its value is dependant upon the amount of internal friction occurring at the same frequency as the imposed stress.

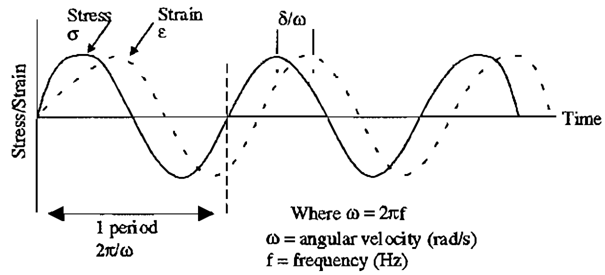

Figure 1. Stress-strain curves for dynamic mechanical analysis

Stress, σ varies as a function of time according to,

$$\sigma(t) = |E|\,\varepsilon_o\,[\sin \omega t \cos \delta + \cos \omega t \sin \delta]$$

or

$$\sigma(t) = E'\,\varepsilon_o \sin \omega t + E''\,\varepsilon_o \cos \omega t$$

The storage modulus is defined as $E' = |E| \cos \delta$ where the modulus is in phase with the applied stress. The loss modulus is defined as $E'' = |E| \sin \delta$ where the modulus is 90° out of phase with the applied stress. Tan δ is thus equal to E''/E' and it indicates the level of internal friction or loss. The dynamic modulus $|E| = \sigma_o/\varepsilon_o$ where σ_o and ε_o are the peak stress and strain.

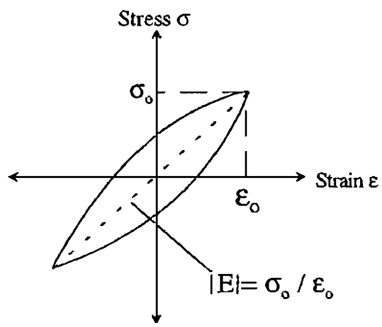

Figure 2. Stress - strain hysteresis loop

In dynamic fatigue tests on panel products in four-point bending, values of $|E|$ and the loop areas are recorded. The DMTA enables the storage modulus E′ and tan δ to be measured as a function of temperature. Some correlation should exist between $|E|$ and E′ and between loop areas and tan δ. Furthermore the difference between skin and core properties can be conveniently evaluated using the DMTA. The fatigue samples are subjected to forced, constant amplitude, sinusoidal loading across the whole panel, whilst the DMTA samples are thin and experience very small strains from a vibrator unit.

2. MATERIALS and EXPERIMENTAL METHODS

2.1. MATERIALS

Three commercial grades of wood based panel products were chosen for fatigue and creep testing in flexure and the dynamic mechanical thermal analysis. These were; a MUF bonded softwood structural grade C4 chipboard, manufactured in accordance with BS 5669 part 2:1989, a grade F2 moisture-resistant OSB, manufactured in accordance with BS 5669 part 3:1992 and a moisture-resistant grade of MDF, manufactured in accordance with BS 1142:1989, bonded with MUF resin.

Prior to testing all the samples were conditioned at 20°C±2°C and ~65% RH to ensure uniform moisture content and reduce variability in moisture-controlled mechanical properties.

2.2. DYNAMIC MECHANICAL THERMAL ANALYSER (DMTA)

The DMTA measures the dynamic modulus and damping behaviour of solids and viscoelastic materials. It is a useful tool for studying changes in morphology and structure of a material, for example the skin and core of panel products and adhesive interfaces. A material can be studied over a chosen temperature range (-100 to 200°C), frequency range (0.01 to 200Hz) and at one of three set strain levels. Tests can be carried out in bending (single or double cantilever), tension, compression or shear. The suitably of one particular mode of deformation depends on the sample stiffness not exceeding the machine's limits. The DMTA records the loss tangent and storage modulus for a sample. If required the loss modulus and complex modulus are computed from these values.

2.2.1. Sample preparation

Samples were prepared from the three candidate panel products. The initial testing was concerned with the flexural properties of samples cut transversely from each candidate panel, see figure 3. All the samples were returned to the cupboard after preparation in order to maintain control over their moisture content. The average sample size was 6.6mm*1.5mm*20mm with a clamp to clamp dimension of 5mm. The length of the sample is fixed by the spacing of the single cantilever bend head on the DMTA. The main axis of the panel was oriented with the sample width. Samples were sanded down to the required thickness.

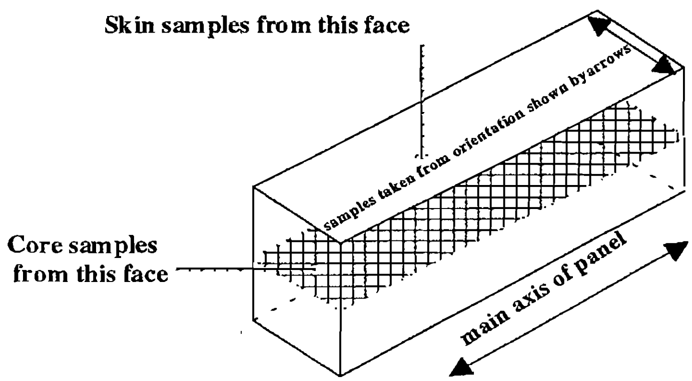

Figure 3. Diagram illustrating the orientation of the sample sectioning

2.2.2. Experimental Details

A Rheometrics mark 1 DMTA operated by a personal computer was used for all the testing. The single cantilever bending mode was selected as this is recommended for initial testing. Three samples from the core and skin of the wood products were taken and tested over a temperature range from 25 to 200°C heating at 2°C/min. The temperature range was chosen to avoid the use of liquid nitrogen. The strain level of x4 is suggested for single frequency temperature sweep experimentation; this relates to a 0.192% strain in the sample. A frequency of 5Hz was selected as this allowed the machine to collect sufficient data within a reasonable time. Problems can arise with insufficient time to collect data when lower frequency levels are selected. A schematic of the experimental set-up is shown in figure 4.

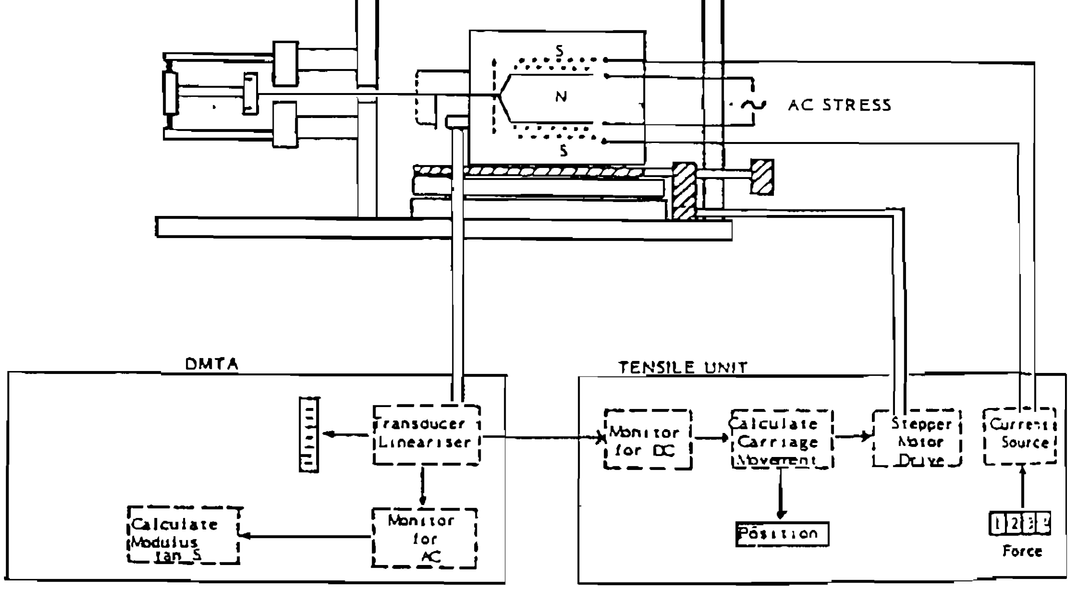

Figure 4. Tensile system schematic operation (DMTA handbook)

2.3. FATIGUE AND CREEP TESTING

Details of the fatigue and creep testing have been described by Thompson et al (1996b). The fatigue and creep response of chipboard, OSB and MDF are usually compared as a percentage of their ultimate bending strength. In order to compare the performance of these three materials at close to equal stress levels, parallel creep and fatigue tests were performed in four point bending. Using the results from Thompson (1996a) two sets of data containing one sample from each of the three materials were selected. For comparison two bending strengths, BS, were chosen: BS ~ 21MPa (set 1) and BS ~ 17MPa (set 2). These values were selected as the requisite data was available for all the materials. Fatigue data was collected using stress-strain hysteresis loops. It was of interest to see whether hysteresis loop area and dynamic moduli could be related to elastic moduli and tan delta results from the DMTA as both are techniques that measure the viscoelastic properties of a material.

3. RESULTS AND DISCUSSION

Dynamic moduli results from the first loop and last loop before failure captured during fatigue testing (Table 1) can be compared with the elastic moduli results obtained from the DMTA testing (Table 2). Whilst the DMTA testing examined the mechanical response of the skin and core layers, the fatigue testing measured the properties of the whole board. It is of interest to see how the skin and core layers of each panel tested can be related to the overall sample stiffness and damage accumulation levels, as indicated by the dynamic moduli and hysteresis loop areas.

Table 1. Hysteresis Loop Data (Pritchard et al, 1996)

	SET 1 (MEAN BS* = 21MPa)				SET 2 (MEAN BS = 17MPa)			
SAMPLE	FIRST LOOP		LAST LOOP		FIRST LOOP		LAST LOOP	
	Dynamic Modulus GPa	Loop Area kJ/m^3	Dynamic Modulus GPa	Loop Area kJ/m^3	Dynamic Modulus GPa	Loop Area kJ/m^3	Dynamic Modulus GPa	Loop Area kJ/m^3
MDF	4.147	4.471	3.847	6.184	4.449	3.215	4.527	3.816
OSB	6.062	4.860	4.547	7.230	6.297	2.461	5.729	3.285
CHIPBOARD	4.838	4.015	4.43	7.411	4.871	3.662	4.429	7.059

* BS = bending strength

Table 2. DMTA Results for MDF, OSB and chipboard

		Log Elastic Moduli (Pa) E'		Tan Delta	
Material	**Sample section**	**30°C**	**200°C**	**30°C**	**200°C**
MDF	SKIN	9.231	8.897	0.0415	0.065
	CORE	8.589	8.171	0.0551	0.1208
OSB	SKIN	9.068	8.694	0.0664	0.1137
	CORE	8.860	8.511	0.0609	0.0889
CHIPBOARD	SKIN	9.262	8.596	0.0578	0.1186
	CORE	8.526	7.821	0.1161	0.2076

3.1. ELASTIC MODULUS RESULTS AND DISCUSSION

3.1.1 DMTA

A general tendency for the elastic modulus to decrease with increasing temperature was observed for all the samples tested (figures 5 to 8 and Table 2). The skin samples exhibited consistently higher elastic moduli compared with the core samples for each material. The MDF and chipboard samples showed a marked difference with respect to skin and core elastic modulus values. This may be a consequence of the skin layers in these panel products having a greater density than the core. It is known that the chipboard produced in a layer structure contains a higher percentage of resin in the skin (11%) compared with the core (5%), this may account for the different elastic modulus values. However, OSB skin and core samples exhibited similar elastic moduli values. This may be due to the lower levels of resin binder (2.5%) used in the manufacture of OSB, resulting in less marked boundaries of high and low resin content occurring between the skin and core layers.

The more homogeneous resin distribution in the OSB and/or the lower resin content resulted in lower elastic moduli for the skin but higher moduli for the core compared with MDF and chipboard. This could also be an effect resulting from greater porosity in the free surface of OSB compared with MDF and chipboard. The overall effect is that OSB is a stiffer panel product than MDF and chipboard. There appears to be the end of a viscoelastic transition stage occurring in the chipboard core sample (figure 7), i.e. the decrease in elastic modulus between 25°C and 50°C. This could be a result of the resin curing, however, this requires further investigation. There exists some uncertainty on the validity of the absolute elastic modulus values measured by dynamic mechanical thermal analysis. The elastic modulus results should therefore be compared in order to rank the stiffness of the skin and core of the three panel products.

3.1.2. Dynamic Moduli

The resin distribution and density profiles of the MDF and chipboard skin and core layers may account for the lower dynamic moduli of these materials compared with OSB. A more uniform yet lower resin content in the OSB layers may explain the higher stiffness of OSB observed in the fatigue testing for both sets 1 and 2 (Table 1). Maximising the wood content and minimising the resin and porosity levels should increase the dynamic moduli. In the case of OSB the particles are large and long in the grain orientation, this may account for the higher dynamic moduli exhibited by this material.

3.2. LOSS TANGENT RESULTS AND DISCUSSION

3.2.1. DMTA

The loss tangent values were all less than 0.22, i.e. the ratio of loss modulus to storage modulus was less than 0.22 for all samples tested (figures 6 and 8). The core samples of MDF and chipboard exhibited greater energy loss through frictional effects than the respective skin samples. OSB showed the opposite result to MDF and chipboard, i.e. the skin had a higher tan delta value than the core. A general tendency for values of tan delta to increase with increasing temperature was observed for all the samples tested. This could be attributed to the increasing temperature in the samples causing a softening of the resin binder, therefore a decreasing storage modulus and consequently an increasing loss tangent. Energy losses through internal friction may arise from chip to chip (chipboard), fibre to fibre (MDF) or flake to flake (OSB) interactions, thus contributing to the increasing tan delta with temperature.

3.2.2. Stress-strain hysteresis loop areas

MDF and chipboard exhibited higher loop areas (e.g. Table 1, set 2) indicating a greater degree of damage accumulation in these samples as a result of the fatigue testing. The results were mirrored in the DMTA tan delta values for the core sections of these materials. Core samples of the MDF and chipboard exhibited greater increases in tan delta from 30°C to 200°C compared with OSB (Table 2). This was analogous to the loop area results where MDF and chipboard showed higher loop area values for the first and last captured loops (set 2). Conversely, OSB with the lower loop areas exhibited the lowest increase in tan delta during dynamic mechanical thermal analysis of the core sections. However, tan delta values from the corresponding skin sections showed that MDF displayed the lowest increase in tan delta during testing followed by OSB then chipboard, although the latter two materials exhibited similar values.

Tan delta values from the core sections of the three samples correlate well with the loop area results obtained from fatigue tests performed when a similar absolute stress level of 17MPa (set 2) was applied to each material. The tan delta values recorded for the skin sections may be more closely linked to the density profile of the three materials, i.e. MDF having the densest skin section whilst OSB and chipboard could be expected to show similar skin density values. The set 1 loop area results for OSB and chipboard may be misleading as data was obtained from 80% stress level tests compared with 50% for the MDF. Fatigue testing at 80% of the ultimate bending strength (UBS) was very rapid, sometimes lasting only a matter of minutes compared with fatigue test at 50% of the UBS where tests lasted over a week. However, the set 2 results were obtained from fatigue tests performed at lower percentage stress levels, i.e. 70% of the UBS for the chipboard, 60% of the UBS for the OSB and 40% of the UBS for the MDF. These tests all lasted an appreciable amount of time allowing a reasonable amount of data to be collected for each sample.

4. CONCLUSIONS

- Elastic storage moduli decreased with increasing temperature for all the DMTA samples tested. The skin sections exhibited consistently higher elastic moduli compared with the core sections for each material.
- Tan delta values increased with temperature for all DMTA samples tested. This is thought to be due to the resin binder softening at elevated temperatures resulting in an increased storage modulus and thus tan delta.

- The lower overall resin level in OSB and a more even distribution of resin in the skin and core sections could account for OSB exhibiting similar elastic moduli in the skin and core compared with MDF and chipboard.
- Tan delta results from core sections showed some correlation with increased loop areas observed during fatigue testing of the three panels. MDF and chipboard exhibited a greater increase in tan delta from 30 to 200°C than OSB. This corresponded well to MDF and chipboard exhibiting higher loop areas compared with OSB.

The technique of dynamic mechanical thermal analysis has provided an additional perspective on the mechanical response of MDF, chipboard and OSB. The initial results obtained indicated that mechanically-driven fatigue testing and vibrationally-driven DMTA produce comparable results. The technique of DMTA enables data to be collected relatively quickly (e.g. one test lasts 1½ hours compared with anything from minutes to weeks for fatigue testing depending on the stress level chosen). It could prove to be a useful tool in the analysis of wood-based panel products relative to the structure and composition of the materials or as a rapid quality control tool. It will be of interest to measure changes in elastic moduli and tan delta values for panel products that have been subjected to flexural fatigue tests.

5. ACKNOWLEDGEMENTS

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Figure 5

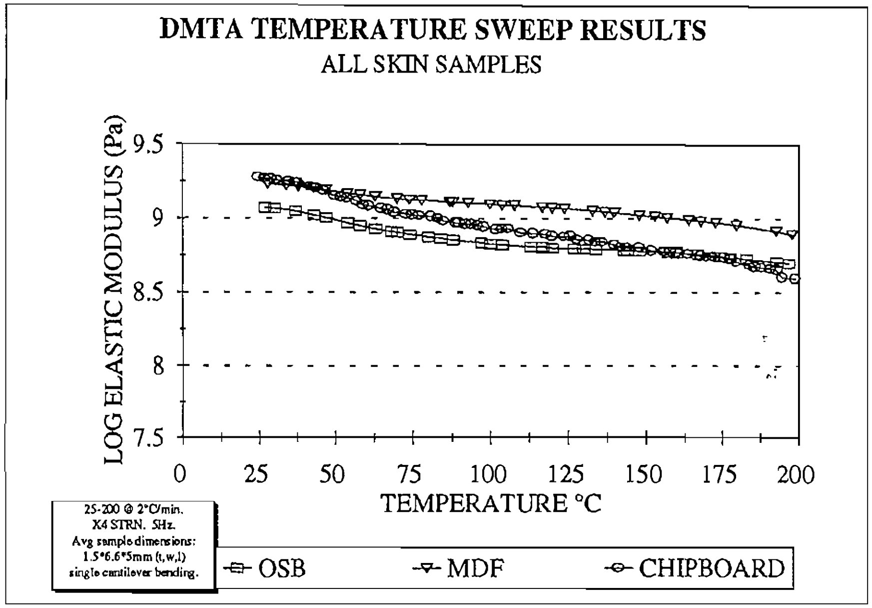


Figure 6

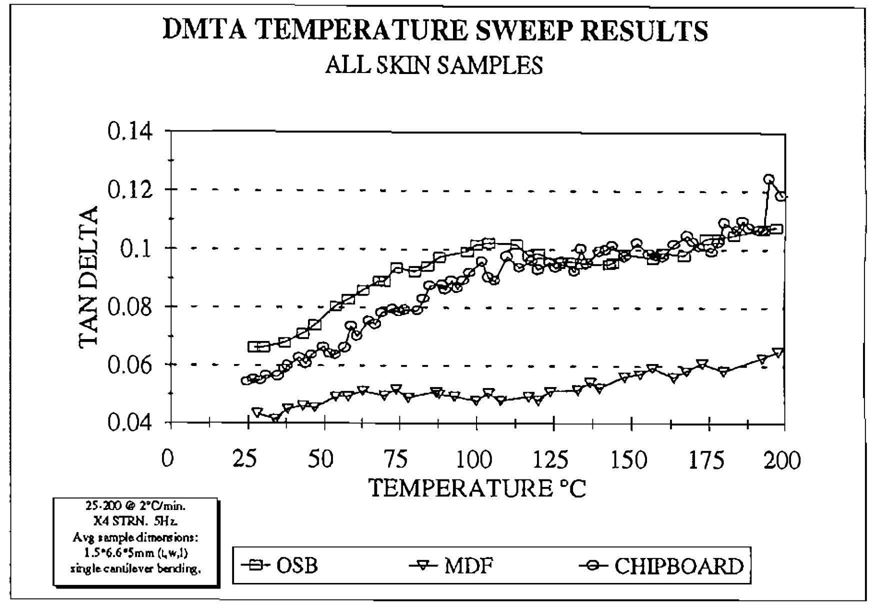


Figure 7

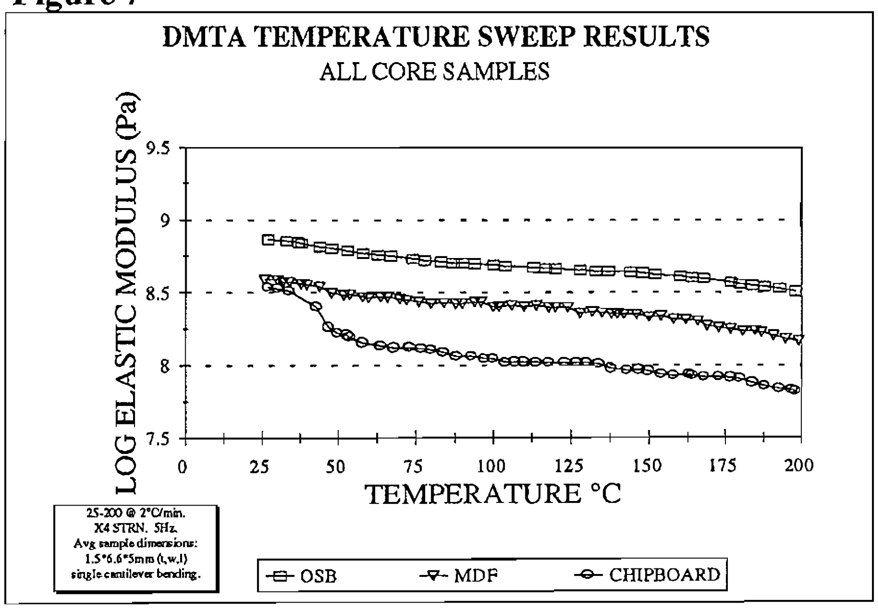
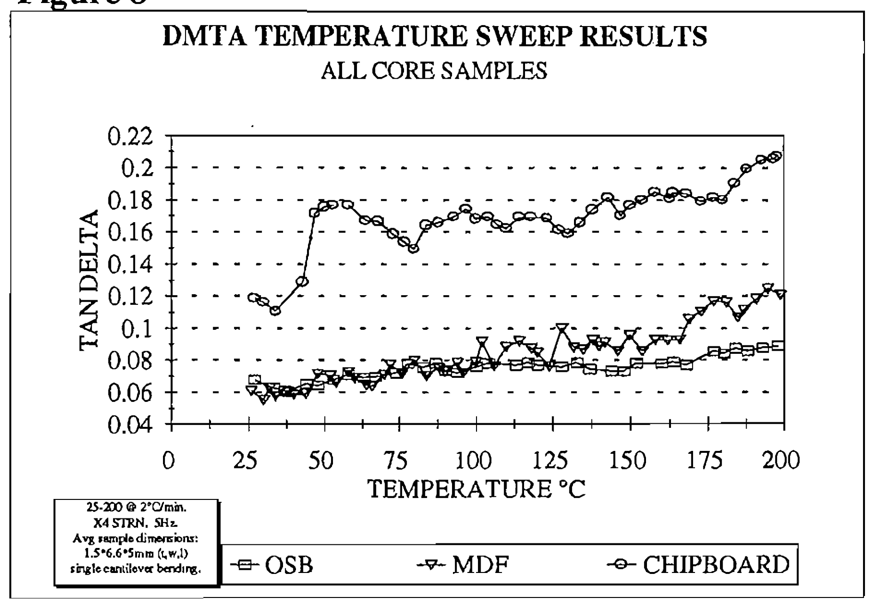


Figure 8



PRODUCTION AND USE OF DECORATIVE SLICED VENEER FROM EAST GIPPSLAND HARDWOODS

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ABSTRACT

The suitability of eight East Gippsland hardwood species for the production of decorative sliced veneer was evaluated. Manufacturing trials were carried out to assess veneer slicing and drying procedures, and the use of decorative veneer for production of veneered furniture panels and profile wrapping. The trials demonstrated that these species could be processed successfully.

INTRODUCTION

A high percentage of the Australian hardwoods has been utilised for structural products, such as domestic framing, decking and fencing. However, because of their hardness, strength, stability and unique appearance, the hardwoods are suited to uses such as furniture, joinery and other appearance products.

In response to growing interest in the use of native hardwoods for high value products, a research study has been undertaken by the Wood Processing and Products Program at CSIRO, Forestry & Forest Products, in collaboration with the Victorian timber and furniture industries, to evaluate the potential use of East Gippsland hardwoods for appearance products. The overall objective of the project is to develop innovative drying procedures and timber specifications, as well as further processing techniques to produce value-added products based on solid wood, laminations, veneers and combinations of low and high grade hardwoods.

This paper presents an evaluation of slicing and drying procedures for the production of decorative sliced veneers from selected East Gippsland hardwoods, and the use of these veneers in the manufacture of veneered furniture panels and profile wrapping (1).

The species included in the study are listed below:

Mountain ash (regrowth) *(Eucalyptus regnans)*
Messmate *(E. obliqua)*
Manna gum *(E. viminalis)*
Shining gum *(E. nitens)*
Yellow stringybark *(E. muellerana)*
Red ironbark *(E. sideroxylon)*
Silver wattle *(Acacia dealbata)*

PRODUCTION OF DECORATIVE SLICED VENEER

1. Flitch Preparation

Veneer quality sawlogs of each of the seven species were selected and cut into billets according to slicer log/flitch specifications (2). A half-round or a quarter round flitch was then sawn from each billet on a breakdown saw. Quarter-round sections were sawn when logs were greater in diameter than 60 cm, otherwise half-round sections were sawn (3). The billets were transported to Gunns Veneers, Boyer, Tasmania, for slicing into decorative veneer. Specialised sawing equipment then was used to shape the flitches according to the standard patterns.

Preheating of flitches to soften the wood and hence improve the quality of cut is an important process in decorative veneer production. For Tasmanian oak and ash, flitches are heated overnight in water at a temperature of 40 - 50°C. Two of the Gippsland timbers, red ironbark and yellow stringybark, were denser and harder than Tasmanian timbers, and they were heated at higher temperatures and for longer times than usual. The heating schedules used and measured veneer density for the seven species are shown in Table 1.

Table 1. Experimental flitch heating schedules for East Gippsland hardwoods.

Species	Water temp. (deg. C)	Duration of heating (hours)	Veneer density at 12% moisture content (kg/m^3) *
Silver wattle	40	16	647 (630)
Mountain ash	40	16	606 (680)
Messmate Feature flitch	40 65	16 6	825 (780)
Shining gum	50 60	16 7	874 (700)
Messmate	50 60	16 3	825 (780)
Manna gum	50	16	704 (750)
Yellow stringybark	50 70 80	15 80 15	818 (870)
Red ironbark	50 70 80 90 70	15 18 18 12 168 (1 wk)	1062 (1130)

* The bracketed figures are the air dry densities for the species taken from K R Bootle, "Wood in Australia: types, properties and uses". McGraw-Hill (1983).

2. Veneer Production

Flitches of each species were sliced on a Keller vertical slicer and a Capital staylog lathe. The test veneers were then dried in a Keller single deck band-dryer at a temperature of 180°C to a final veneer moisture content target of 10%.

There appeared to be no significant difference in the capability of the two slicing machines except when processing **red ironbark.** The isolated cases of rough cutting were associated with pronounced inter-locked spiral grain in some of the crown-cut ironbark material. In one instance serious instability developed when crown-cutting on the stay-log lathe. The troublesome flitch was then removed and sliced without incident on the Keller slicer.

The **silver wattle, messmate, mountain ash, manna gum** and **shining gum** like the local Tasmanian ash/oak product, behaved well through slicing and drying.

3. Quality of Veneer

Traditionally, sliced veneer has been graded into three grades (face, natural and back) on the basis of the amount of defects and "features" (1). The amount of "features" in the East Gippsland veneers was rather high. Typical characteristics encountered in the veneers are summarised in Table 2.

Table 2. Typical characteristics of East Gippsland sliced veneers

Species	Veneer characteristics
Mountain ash	Gum
Messmate	Borer holes (*), gum, hobnail, fiddleback grain
Manna gum	Hobnail (**), gum, borers
Shining gum	Gum, epicormic shoots,
Yellow stringybark	Borer holes, gum, hobnail, interlocked spiral grain
Red ironbark	Interlocked spiral grain
Silver wattle	Insect/grub damage, epicormic shoots

(*) : The borer holes were left by the pinhole borer Ambrosia beetle.
(**) : The term hobnail refers to tracings in the wood grain left by a grub (*Bucculatricidae family*).

Face grade veneers of **mountain ash** and **manna gum** generally were ivory in colour, straight-grained and tended to be featureless in appearance, resembling the Tasmanian product - Tasmanian oak.

With their light to medium brown colour and generally straight grain **messmate** and **shining gum**, would be equivalent to Tasmanian oak. The shining gum was distinguished by fairly conspicuous growth rings and unlike messmate provided a fineline stripe in quarter-cut veneer and well-defined crown figure in crown-cut. Veneer with fiddleback figure was obtained from the butt portion of a messmate tree.

Unlike the species mentioned so far, both **red ironbark** and **yellow stringybark** tend to be figured woods. Both have interlocked spiral grain and as a result showed well-defined ribbon grain on quarter-cut surfaces. In addition, grain waviness in the tangential plane often added "crossfire" to the ribbon grain. The colour of the yellow stringybark was an even yellow-brown at times tending to gold, while the ironbark was generally dark red with some variegation.

The entire **yellow stringybark** consignment was marred by extensive Ambrosia borer attack. Although in every case evidence was found of borer attack having taken place in the standing tree, some attack might have occurred in the period between sawing of flitches and slicing. Reportedly, borer-free yellow stringybark is obtainable from certain areas in East Gippsland and so, at this point it would be premature to write-off this otherwise promising species.

Silver wattle was straight-grained and generally had a slightly streaked pale brown colour similar to that of the palest wood of blackwood (*Acacia melanoxylon*). The wood also had the characteristic lustre of blackwood.

There is a growing demand within the furniture industry in heavy "featured" veneers. To satisfy the industry interest, a few flitches of messmate showing localised burl formations were sliced successfully to produce crown-cut veneer. The veneer showed a coarse "bird's eye" figure.

PRODUCTION OF VENEERED PANELS AND PROFILE WRAPPING

1. Production of Decorative Veneered Panels

Veneered panel manufacturing trials were carried out at Presswell Panels Pty Ltd, Campbelfield, Victoria. For each species, two bundles of crown-cut and two bundles of quarter-cut veneers were used for the trials. The bundles of matched veneer leaves were cut to a desired jointing width on a "Casati" guillotine and "butt joined" on a "Kuper" stitching machine using three common methods of joining: book matching, slip matching and reverse-slip matching (4). Eighty four veneer layons were prepared for pressing.

The veneer layons were laminated on typical substrates, i.e. particleboard and medium density fibreboard (MDF) using pre-catalysed PVA cross-linking glue. A standard panel size 2400 x 1200mm x 18mm was used.

A pressing line "Siminpianti" using a radio-frequency heating was used for gluing and pressing operations (5). A glue spread $50 g/m^2$ was used. The panels were sanded 24 hours after pressing to allow the panels to stabilise.

No problems occurred during the laminating of the veneers. Typical manufacturing procedures were used for all veneer species apart from red ironbark which required a slightly longer pressing time (53 sec, as opposed to 48 sec used for other species).

Example of veneered panel is presented on Figure 1.

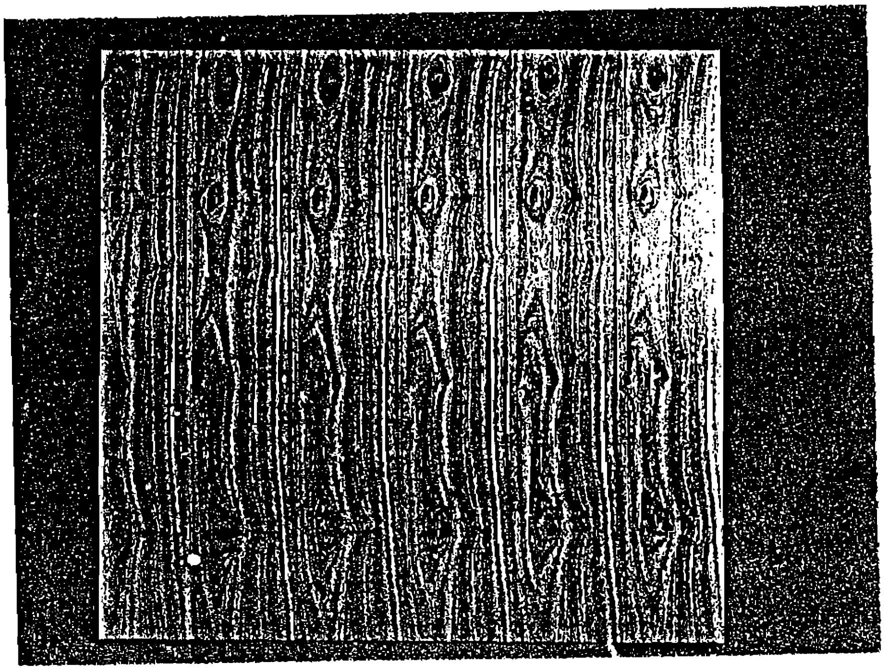

Figure 1. Example of veneered panel (ironbark crown-cut veneer)

2. Profile Wrapping of Veneers

The use of veneer for wrapped mouldings has a significantly growing market, particularly in architectural applications. Mouldings of various profiles made from solid wood or a reconstituted wood product such as MDF are used as a substrate for making products such as architraves.

One bundle of each veneer species was selected for production of veneer wrapped profiles.
The profile wrapping trials consisted of the two following operations: preparation of veneer for wrapping (veneer trimming into required width, finger jointing of veneers into a continuous veneer tape, veneer fleece backing and sanding), and wrapping of the veneer over a moulded profile. The profile wrapping was carried out at Marbut Pty Ltd, Seymour, Victoria, on a "Barberan" profile wrapping machine. Hot melt EVA glue was applied to the veneer tape which was pressed by a series of pressure rollers onto previously shaped MDF component.

All stages of the manufacturing process proceeded without any problems. No changes in processing methods or parameters were required.

Example of veneer wrapped profile is presented on Figure 2.

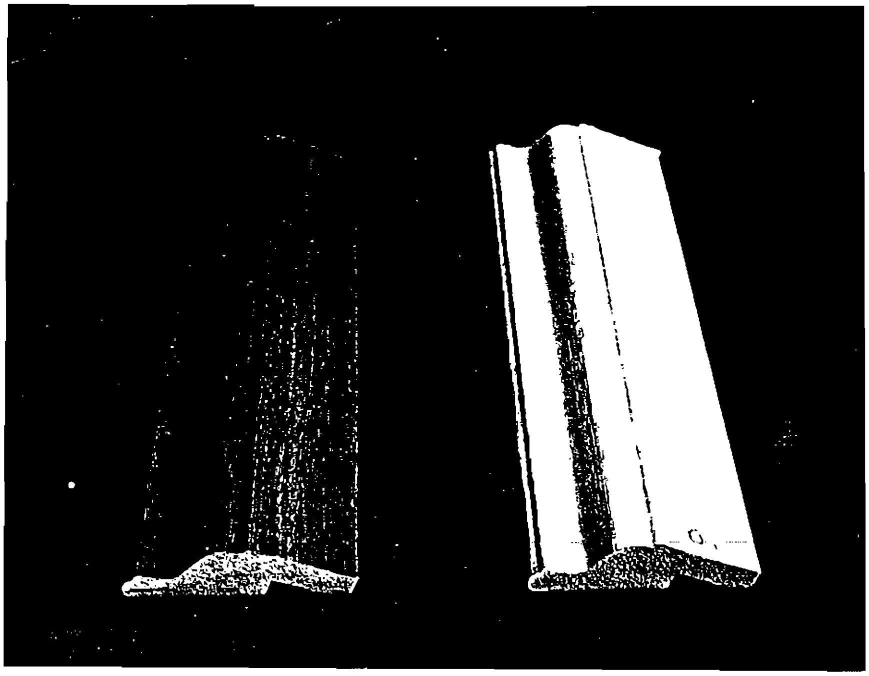

Figure 2. Example of veneer wrapped kitchen cabinet corners.

3. Performance of Veneered Panels and Profiles

The veneer bond strength and veneer bond durability of the veneered panels were evaluated according to AS/NZ 4226:1996 (6). All tested samples met the standard requirements.

In addition, the performance of the veneered panels and veneered profiles in changing conditions of environment was assessed (7). No sign of veneer delamination or splitting was observed in tested samples

CONCLUSION

Processing through slicing and drying was trouble-free for all species except red ironbark and yellow stringybark. Poor veneer handling properties associated with the high density of red ironbark and yellow stringybark were largely overcome by raising flitch preheating temperature and extending heating time.

Gum vein was the main "feature" for **mountain ash** as was Ambrosia attack for **messmate.** **Silver wattle** suffered suspected grub attack and an excess of epicormic shoots that left pinknot-like markings on the veneer

No problems occurred during the production of veneered panels Apart from red ironbark veneer which required a slightly longer pressing time, the laminating process for other veneers did not differ from typical veneer laminating procedures

Profile wrapping with East Gippsland veneers did not cause any manufacturing problems.

Tested samples of veneered products passed standard requirements for the veneer bond strength, bond durability and performance in changing conditions of environment.

Decorative veneered products manufactured from East Gippsland veneers created great interest within the furniture industry in Victoria. Feasibility studies have been undertaken by the furniture and timber industries on the establishment of veneer slicing facilities in East Gippsland.

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RADIATA TANNIN ADHESIVES - THE ROAD TO COMMERCIALISATION

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ABSTRACT

The availability of radiata pine bark, the size of the market for Australian reconstituted wood products, and their adhesives statistics are presented. The research and development of wood adhesives from radiata pine bark are briefly reviewed. The recent work of CSIRO, in collaboration with CSR, resulting in the establishment of a radiata tannin extraction pilot plant is described.

INTRODUCTION

Radiata pine (*Pinus radiata* D.Don) is the most important softwood species and the dominant plantation species for wood production in Australia. The natural productivity range of radiata pine is broadly 15 to 35 m^3/ha/year in Australia.

According to Quarterly forest products statistics (ABARE, March 1995), the total area of radiata pine plantations was 0.72 million hectares in Australia. Approximately 6.7 million m^3 of radiata pine round wood was removed from the plantation forests over the period of one year between 1993 and 1994, of which 4.0 million m^3 were used for sawn and veneer logs, 1.7 million m^3 for paper and paperboard, 0.8 million m^3 for woodbased panel products and the remaining 0.2 million m^3 for other uses. At the same time, radiata pine bark was estimated to have been generated at a rate totalling approximately 0.8 million m^3 per annum at several wood processing centres. Furthermore, the yield of the radiata pine bark is expected to double in the next 10 years.

Since Dalton's pioneering work on wood adhesives from tannin extracts of wood and bark in the 1950's (1,2), extractives from radiata pine bark have been studied with a view to producing water-proof wood adhesives. These studies revealed that radiata pine bark contains significant amounts of reactive polyphenols (polyflavanoids) which can be useful as a basis for water-proof and durable wood adhesives when reacted with formaldehyde.

CSIRO has been collaborating with CSR Timber Products since September 1994 with a view to commercialising the production of water-proof wood adhesives from radiata pine bark. This paper outlines the problems being experienced and their solutions, during the course of the establishment of a 200 tonnes/year capacity tannin production pilot plant in Oberon, New South Wales, Australia.

BACKGROUND OF RADIATA TANNIN ADHESIVES (RADTAN) PROJECT

In 1990-1991, the total wood consumption excluding railway sleepers and paper & paperboard was 4.9 million m^3 of which 4.1 million m^3 was used for solid wood, with the remaining 0.8 million m^3 used for reconstituted wood products such as plywood and particleboard (ABARE, December 1995). However, in 1994-1995, the total wood consumption was 6.2 million m^3 of which 4.8 million m^3 was for the solid wood and 1.4 million m^3 was used for reconstituted wood products. These statistics indicate that the consumption of reconstituted wood products increased by 84 %, compared with only 16 % for solid wood over the past 4 years.

In 1994-1995 the Australian reconstituted wood products manufacturing industry produced almost 1.5 million m^3 of reconstituted wood products, of which more than 0.85 million m^3 was particleboard, 0.15 million m^3 plywood and 0.45 million m^3 medium density fibreboard (ABARE, December 1995) resulting in the use of more than 70,000 tonnes of wood adhesives, for which industry paid more than A$90 million.

In South Africa, tannin extraction plants using black wattle (*Acacia mearnsii*) bark were established in the early 1900's for marketing tannin to the leather industry. Basic and fundamental research on wattle tannin adhesives was carried out at CSIRO in Australia which showed wattle tannin adhesives could produce a strong, water-proof bond with veneers of a number of species (5). Commercialisation of these wattle tannin adhesives followed in the late 1960's in Australia and in the early 1970's in South Africa. Since 1970 the Australian particleboard manufacturing industry has been using wattle tannin adhesives for the manufacture of particleboard flooring. At present, Australian industry imports more than 7,000 tonnes of wattle tannin from South Africa, paying more than A$7 million per annum.

With the emphasis on more efficient utilisation of forest resources, CSR has decided to evaluate an established extraction process, based on fundamental studies of the chemistry of radiata tannin extraction developed at CSIRO. The aim is to substitute the wattle tannin from South Africa with radiata tannin.

PROBLEMS IN THE USE OF RADIATA BARK FOR TANNIN ADHESIVES

Problems associated with low yields, excessive viscosity and variable quality of tannin extracts from bark have previously prevented the industrial use of radiata pine bark in Australia, whilst in New Zealand the major problem experienced was associated with variable quality of high yield tannin extracts.

The yield of tannin extracts varies considerably depending on the bark source, the condition of bark storage, and the method and conditions of extraction (6). It is also dependent on the temperature, the particle size of the bark and on the pH of the solvent. Hot (100° C) water extracts from the small-sized (<0.6 mm) bark gave the highest yield (25.7%), whilst that from the large-sized (1.0-1.4 mm) gave only 16.2% (7). Although the commercially-feasible yield is at least 15% in the Australian industry, this type of laboratory extraction using a Soxhlet extractor is not feasible for industrial application.

In contrast to the more fibrous wattle bark, radiata pine bark tends to form small particles during grinding, which results in a tightly packed layer during percolation. Therefore, the extraction liquid passes very slowly through the bark, resulting in very low extractives yields or very long extraction times. This is particularly evident as the particle sizes become smaller.

Radiata pine bark, which was passed through a 4 mm open screen of a Wiley mill, gave approximately 10% hot water extractives yield using an ordinary batch extractor, whilst bulk extraction of larger bark particles (but less than 27 mm) gave only 6.3% yield (8). It has not been possible to obtain high yields using conventional batch extractors.

The second problem encountered was in formulating wood adhesives, because of the high viscosity of high yield extracts. For example, the viscosities of 100° C aqueous extracts at 40% solids content and pH 4 were found to be 18,000 mPa.s at 25° C. In this case, high yield 100°C aqueous extracts could not be formulated as wood adhesives due to this excessive viscosity. A number of methods of reducing viscosity have been proposed but the most common method is based on the treatment of radiata pine bark extracts with sodium sulphite or sodium metabisulphite (3). An ultrafiltration study revealed that the highest molecular weight fraction ($>10^6$) was the major viscosity control factor for aqueous solutions of the radiata tannin extracts (9).

The third problem was the variable quality of wood adhesives derived from the bark extracts. Aqueous extracts from radiata pine bark consist of polyflavanoids reactive with formaldehyde and non-reactive low molecular weight carbohydrates and polyphenols (6). The variable quality of adhesives is largely due to the purity of polyflavanoids in the extracts and to the variation in molecular weight distribution of the polyflavanoids.

In order to overcome problems relating to the excessive viscosity and the variable quality, an ultrafiltration process has been proposed and patented (10).

TANNIN REACTIVITY WITH FORMALDEHYDE

It is well-known that the extraction of radiata pine bark with solutions of increasing alkali concentration increases the yields of bark extracts (11,12). The highest yield (>65%) of the extracts was obtained with 1% NaOH extraction of small (<0.6 mm) bark particles (7). The use of NaOH extracts from various softwood barks for wood adhesives has been reported (13,14,15). However, these NaOH extracts required fortification with synthetic PF resins to obtain acceptable gluebond quality.

These facts prompted questions about the stability under alkaline conditions of the radiata bark extracts. Under alkaline conditions catechin is converted quantitatively to catechinic acid resulting in the loss of the A-ring reactivity with formaldehyde. Relatively rapid formation of catechinic acid from catechin was observed at 100°C and pH >10, and no significant glue bond was obtained when high pH 10.4 extractives were formulated (17). Furthermore, the alkaline treatments of procyanidins, procyanidin polymers and radiata bark extracts decreased their reactivities with formaldehyde to a great extent (16). Consequently, when the higher reactivity of the phloroglucinol A-rings of the polyflavanoids is desired for gluing, the extracts should not be subjected to strong alkaline conditions.

In New Zealand, commercial tannin extraction was carried out using an 8,000 tonnes/year capacity tannin plant over a period between 1981 and 1987. The plant used alkaline aqueous solutions (mostly sodium carbonate and sulphite) to obtain higher yield and reduced viscosity of the tannin extracts. However, these tannins failed to produce high quality wood adhesives of uniform quality.

TECHNOLOGY AT CSIRO

Considering all the factors leading to lower extractives yields, excessive viscosity and variable quality of extracts, a new technology to produce high quality wood adhesives based on high yield extracts from radiata pine bark has been developed by CSIRO. The CSIRO process tackles these problems by extracting larger particle sizes using a new extractor, employing a two stage extraction together with sulfite treatment and altering molecular weights of extracts to a more uniform distribution. An example of this process is as follows.

Commercial air-dried bark samples were ground to pass a12.5 mm screen and extracted by a four-stage squeeze-extraction using hot water and pH 8.3 (NaOH) aqueous solution as solvent. A total extractives yield of 29.4% was obtained. Adhesives derived from these extracts without any synthetic fortification provided the highest gluebond quality (17). The principles of this technology are based on obtaining hot water extractives (14.8%) from the bark first, and then slightly alkaline (pH 8.3) high polymer extractives (14.6%) which are sulfited. These two extractives were combined for adhesive formulations. Thus, the sulfitation is selectively used to reduce the molecular weights of the undesirable high molecular weight extractives responsible for excessive viscosity in the bark extracts (18,19).

RESEARCH AND DEVELOPMENT AT CSR

When CSR purchased Softwoods Holdings, they also acquired the research into the use of tannin from radiata pine bark. Over the past 30 years, Peter Crammond had a vision to extract and use radiata tannin (Radtan) in particleboard. By the middle of the 1980's, CSR had run pilot plant extractions and factory board trials at Mt. Gambier using an extraction process patented by Chem Eng Contracts. This process delivered acceptable yield and concentration of tannin. However, for the extract to be useable, it needed to be dosed with 17% alcohol (to reduce viscosity) and paraformaldehyde had to be added as the hardener (20). Neither alcohol, nor paraformaldehyde were acceptable chemicals in our factories and so further work was undertaken to improve the extract for factory application.

TANNIN EXTRACTION PILOT PLANT

After considerable effort, CSR came to the realisation that their failure to produce good and uniform quality extracts from their pilot extractor was due to a lack of knowledge of the fundamental chemistry of radiata tannin. At this stage they became aware that CSIRO Division of Forest Products had developed and patented an extraction methodology which would produce a consistent quality extract. To produce this extract, the CSIRO process was considered to more difficult to scale-up than the CSR diffusion process.

CSR Timber Products used the services of CSR Sugar Central Laboratory to search for a suitable alternative (existing) extraction process. From laboratory-scale column trials, they found that acceptable yields and concentrations could be achieved using a counter-current diffusion process. In these trials they were also able to achieve yields of over 30% at acceptable concentrations.

There are a number of extractors using this principle. In fact, CSR has two extracting sugar from sugar cane. These were too big for our needs and we concluded that the equipment used in oil seed extraction would be sized more appropriately.

A pilot plant was built using a small Krupp Carousel extractor and was commissioned in January 1996 at a cost of $850,000.

The pilot plant takes raw bark, and runs it through a shredder and hammer mill allowing the particle size to be varied. So far, our best results are with a mean particle size of 2 mm. The milled bark is conveyed into a screw conveyor where the bark is saturated and preheated with steam to 97° C. The bark is then delivered to a carousel extractor chamber. The filled bark chambers rotate in a clockwise direction, while the washing liquid travels in the opposite direction.

In the pilot plant there are 12 bark cells. Five are used for hot water extraction and three for caustic extraction. The remaining cells are for drainage and bark discharge.

The caustic extract is further processed by refluxing for 2 hours with sodium metabisulfite (5% on tannin), then blended with the hot water extract before evaporation.

The whole process is PLC (process logic controller) controlled using Citect software.

The purpose of the pilot plant is twofold. First, it can provide operating data for the specification and design of a full scale plant. Second, we can produce sufficient extract to conduct small board trials in the factory to evaluate the quality of the extract. Our first extraction runs did not reflect the great extraction yields and concentrations that we had seen in the laboratory work at Central laboratory. However, we were able to produce sufficient extract to conduct a small factory trial, where we produced over 200 sheets of yellow tongue flooring. Results were very pleasing for our first trial, exceeding our expectations.

At that point we decided not to conduct any further factory trials until we raised the yield and concentration of the process to economically satisfactory levels.

CSR Timber Products is pleased to say that over the past 6 months through a process of optimising variables we have taken yields from 10% to over 25% and concentration from 3% to over 10%.

FUTURE DIRECTIONS

Our next step is to consolidate our optimum conditions and then make sufficient extract for more factory trials. Depending on these results, we will determine future direction and priorities.

CSIRO has also developed an effective hardener which is compatible with Radtan. Unfortunately, it is quite an expensive part of the total resin system. We believe this cost needs trimming.

At this stage, we have been selective in the type of bark used as we have found significant variation in tannin quality with bark. Further work will be needed to overcome the raw bark variation issues.

Once we have confirmed our process and tannin quality is sound, we will be designing and costing a full scale plant along with construction timings. This information will be consolidated for final sign-off and approval by the board of CSR.

LEARNINGS FROM A CSR PERSPECTIVE

- The selection of the partner is as important as the technology.

- The technology is not as good is the supplier thinks or claims.
- Reproducibility and predicability are hard to get in a pilot plant.
- The project leader needs total support from the organisation.
- To get the organisation's support the leader needs to be credible and be prepared to communicate the good and bad news regularly.
- Results often take longer than anticipated.

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WHAT COMES AFTER PHENOLIC-TYPE ADHESIVES FOR BONDING WOOD TO WOOD ?

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ABSTRACT

The properties of conventional formaldehyde-based wood adhesives are reviewed in relation to the recent CSIRO's development of "universal" type phenolic resins as wood adhesives. Considering the demand for more efficient and versatile wood adhesives, isocyanate-type wood adhesives are discussed with a view to be a substitute for conventional formaldehyde-based wood adhesives in the future.

INTRODUCTION

Due to ecological and environmental pressures, the increasing demand for wood and the diminishing supply of high quality large-diameter logs, the production of reconstituted wood products plays an increasingly important role in the efficient utilisation of forest resources. This requires wood adhesives for such products as particleboard, plywood, laminated veneer lumber (LVL), medium density fibreboard (MDF), glulam and so on.

Wood-based panel production in Australia was 1.5 million m^3 (market value of approximately $ 900 million) over a period of one year between 1994 and 1995 (1), for which the Australian reconstituted wood industry used more than 70,000 tonnes of wood adhesives (market value of more than $ 90 million). Phenol- (PF), resorcinol- (RF), tannin- (TF), melamine- (MF) and urea-formaldehyde (UF), and their combinations such as PRF and MUF have been traditionally used in the Australian reconstituted wood manufacturing industry.

As formaldehyde has a pungent odour and causes health problems such as eye irritation and respiratory discomfort, the release of formaldehyde from reconstituted wood products is a problem for the industry. It has been known that reconstituted wood products bonded with UF and to lesser extent MUF adhesives release significant amounts of formaldehyde, whilst the release of free formaldehyde from those products bonded with PF and TF adhesives is almost negligible.

Since the Wood Adhesives Group was formed at CSIRO, Division of Forest Products in 1988, the Group has been developing "universal" type PF resins which have been synthesised on the basis of the special "molecular designing" concept (2) and some of them have already been successfully commercialised.

This paper is a review of the conventional wood adhesives and of isocyanate adhesives as possible substitutes for the phenolic type formaldehyde-based adhesives.

ADHESIVES FOR BONDING WOOD TO WOOD

The need to bond together pieces of wood has been recognised from the earliest times of Egyptian history in 1500 BC. Throughout the ages adhesives from natural origins such as animal glues, casein, and starch have been used. Although most of these adhesives have been largely replaced with synthetic polymer adhesives, some of them such as lacquer are still being used for specific purposes because of their appropriate properties.

Although they performed well under dry and cool conditions, these natural adhesives lacked durability when used in exterior exposure situations. However, most criticism of their performance in the past is a reflection of their misuse under unsuitable conditions.

The present century has seen the replacement of these natural adhesives and the majority of wood adhesives are now synthesised using formaldehyde-based thermosetting resins, which were developed between 1930 and 1945.

Synthetic polymer adhesives are divided into four groups; thermoset, thermoplastic, elastomer and composite. Major thermoset adhesives are formaldehyde-based adhesives such as PF, RF, MF, MUF, UF and their combinations, which are used as common wood adhesives in the Australian reconstituted wood manufacturing industry.

PROPERTIES OF WOOD ADHESIVES

Wood adhesives commonly used in the Australian reconstituted wood industry and their generally accepted durabilities have been summarised previously (2). The thermoset formaldehyde-based wood adhesives such as PF, RF, MF, MUF, UF and other combinations , once cured, give a rigid glueline and are generally considered not to creep under conditions of long term stress.

According to the Australian Plywood Bond Type Classification (3), gluelines bonded with synthetic phenolic and natural tannin adhesives are classified as Type A which can pass a 72-hour boil test. The gluelines can be expected to survive for more than 50 years under fully exposed and long term stress conditions.

One of the major disadvantages of UF adhesives is their susceptibility to hydrolytic degradation of the cured resin in the presence of moisture and/or acids, especially at moderate to elevated temperatures.

MF adhesives are very attractive on the grounds of their better resistance to moisture in the cured state and the use of shorter press times than those necessary for PF resins. However, the adhesive is expensive, about 3.5 times the price of UF and about 20-25 % more expensive than PF resin when based on 100% resin solids. Therefore, the usual practice is to dilute the melamine with urea which are called MUF resins, so that the prices of MUF resins would be approximately 2.5 times the price of UF resins (4).

The bond strength of PF resins is high and deterioration at elevated temperatures in the presence of moisture is slight compared with UF and MUF adhesives. However, resin costs are high and current prices are about 2.8 times those of UF resin based on 100% resin solids (4).

Wood adhesives based on PF, RF and TF or their combinations have been recognised as being most suitable for producing wood to wood bonding for external and structural applications, because phenolic type wood adhesives are presently the only fully structural adhesives capable of performing under all climatic conditions (5,6). The fully structural adhesives can be used in all structural wood composites or structural wood panels where any of the following applications involve either long term exposure to wet or damp conditions or long term stress.

However, compared with UF, MF and MUF adhesives, conventional PF wood adhesives are slower curing and less tolerant to varying wood moisture contents and thus more limited in their allowable gluing conditions. Furthermore, PF wood adhesive technologies developed in other parts of the world are not always applicable for use in Australia. Reasons for this situation can be related to the fact that most reconstituted wood manufacturing factories in Australia are relatively thinly scattered far from resin manufacturing factories hence PF resins require much longer storage stability, and the Australian wood industry has had to utilise many variable quality wood species whose densities vary from medium to high, compared with those in most other countries.

The Wood Adhesives Group at CSIRO Forestry and Forest Products has been developing PF adhesives which are capable of successfully bonding a wide range of reconstituted wood products over a wide range of gluing conditions.

PF RESINS WITH MULTIFUNCTIONAL PROPERTIES

Conventional phenolic resins for use in the manufacture of most reconstituted wood products are known as resoles and are usually prepared by reacting phenol with formaldehyde in the presence of an alkaline catalyst such as sodium hydroxide or potassium hydroxide. The molar ratio of formaldehyde to phenol (F/P ratio) used is typically from about 1.6 to 2.4 for plywood adhesives in Australia.

The viscosity of the reaction mixture rises as the reaction proceeds, due to the formation of phenol-formaldehyde polymers resulting from reaction between methylol groups and unsubstituted positions of phenol with the formation of methylene bridges between phenolic nuclei.

The reaction is continued after the addition of all reactants until the desired final end point viscosity is achieved and yields resoles. These resoles are hardened by the application of heat and pressure resulting in the formation of very highly crosslinked thermoset materials. In this form they have negligible creep, are completely insoluble in most solvents, no longer flow or melt under the further application of heat, but more importantly are incapable of being hydrolysed by water, in contrast to other commonly used formaldehyde-based resins such as UF, MF or their combination (MUF).

Advantages of using UF adhesives are low cost, and the ability to cure quickly at lower temperatures and to tolerate wider gluing conditions. However, since the durability of the glueline bonded with these UF adhesives is very low, UF wood adhesives in Australia are used only in the manufacture of particleboard and MDF for furniture or interior and non-structural applications. Although MF and MUF wood adhesives have little advantage in their costs compared with PF adhesives, their curing speed and their tolerance for gluing variables are better than those of PF wood adhesives. The durability of the glueline bonded with MF and MUF is classified as Type B provided there is sufficient melamine in the MUF to pass a 6-hour boil test, instead of the 72 hours required for PF adhesives. Type B wood adhesives are used for non-critical structural wood bonding where exposure to weather or high humidity will be 2 years of less, instead of 50 years and more as with PF adhesives.

Furthermore, much longer resin storage stability is required in Australia. Multi function PF resins may be defined as functions primarily relating to fast-curing, wood moisture and species tolerance and long storage stability. Furthermore, these resins should be able to tolerate a wide range of assembly times and also be able to be used for plywood and LVL without major changes in adhesive formulation.

CSIRO Forestry and Forest Products has successfully synthesised PF resins with enhanced properties by reactions of phenol (1.0 mol) with formaldehyde (1.8 - 2.4 mol) using various alkali catalysts and the specific characteristics of these multifunctional PF resins *vis* adhesive formulation, gluing conditions and gluebond quality, have been described previously (7).

The gluing results demonstrate the ability of these CSIRO PF resins to satisfy quite different gluing tasks such as fast-curing and adaptability to variable gluing conditions. Furthermore, preliminary tests have also shown the ability of these resins to tolerate average veneer moisture contents over a range from less than 3% to 12% . Work is in progress to enable a complete understanding of the detailed chemical nature of these resins through the use of NMR and GPC techniques.

The CSIRO PF resins have great potential for further utilisation in other reconstituted wood products such as MDF and particleboard and preliminary results have been very promising. PF wood adhesives using the CSIRO resin technology are now being commercialised for LVL and plywood production in Australia.

CHEMICAL REACTIONS OF ISOCYANATES

Isocyanates, characterised by the -N=C=O group, were first synthesised by Wurtz in 1848. They remained very curious compounds until 1937 when Bayer synthesised the first urethane. Since the Second World War, isocyanate/polyurethanes have enjoyed a remarkable growth (8). Today, many both flexible and rigid foams, coatings, polymeric castings, and also adhesives based on isocyanate chemistry are synthesised.

The isocyanate (-N=C=O) group is capable of reacting with almost any active hydrogen under either acid, or preferably alkaline, conditions. The reaction most commonly being used in isocyanate chemistry is with a hydroxyl group to yield a urethane.

The urethane structure, also called a carbamate, is fundamental to many polymers utilising isocyanates. Polymeric substances are formed when a difunctional isocyanate reacts with a difunctional alcohol. Amines can also react with isocyanates to yield a urea structure.

Isocyanates react very readily with water to form primary amines and carbon dioxide. This is important because the amine itself is quite reactive with isocyanate and urea. When the isocyanate group reacts with a urea, a biuret group is formed. Furthermore, isocyanates can react with urethanes to yield an allophenate. Finally, isocyanates react with isocyanates to form various cyclic structures.

BONDING WOOD TO WOOD USING ISOCYANATES

Since resins based on MDI (4,4'-diphenylmethane diisocyanate) have a very low vapour pressure at room temperature, have a consistent viscosity in the low molecular weight ranges, and are relatively inexpensive considering reduced glue solids required compared with PF resins, they have been used as a preferred type of diisocyanate for particleboard manufacture.

According to Ball and Redman (9). references dating to 1951 showed that isocyanates would be effective binders for wood. Deppe and Ernst (10) demonstrated the possibilities of the isocyanate resins for bonding wood to wood in particleboard manufacture.

Following the particleboard manufacturing industry, isocyanates have been used for bonding wood to wood in the finger-jointing and wood lamination industry, particularly in Japan where new generation isocyanate-polyol reaction products (urethane prepolymers) have been developed (11).

Isocyanates are fast-acting, have good water resistance, and can be used at low levels of application. Furthermore, it is possible to make boards at moisture contents much higher than those with UF or PF resins (12,13,14,15). An outstanding characteristic is that isocyanates can glue virtually any wood species (16). However, isocyanates are somewhat more sensitive to extended assembly time due to their fast curing.

The outstanding characteristic of isocyanates is basically their ability to react with hydroxyl groups to form the urethane structure. One of the first models to explain the excellent properties of isocyanate boards at the very low resin levels was a direct covalent bond with cellulose and lignin hydroxyls (17). The excellent board performance at low resin levels was previously presumed to be most likely due to the formation of urethane linkages between isocyanate and wood hydroxyls. The very fast press cycles may very well be caused by the water-NCO reactions yielding an amine which would tend to react very quickly with available isocyanate yielding urea bonds. Structural strength probably is related to the crosslinked network made possible by secondary reactions leading to polyurea and, in some cases, isocyanurate linkages.

Solid state NMR spectroscopic techniques together with DSC (differential scanning calorimeter) measurements were applied to analyse the nature of the isocyanate (MDI) and wood bond. The results revealed that MDI binder had a much greater depth of penetration than PF resins resulting in a larger interphase region between wood and MDI binder. The solid NMR results showed that MDI binder had a large effect on the bulk molecular motions of wood compared to PF resins. Furthermore, DSC measurements showed reaction exotherms between wood and MDI binder while none were observed for the PF wood samples (18).

TOXICITY OF ISOCYANATE ADHESIVES

The toxicity of common chemical coumpounds is usually described using LD_{50}. The term LD_{50} is the lethal oral dose (mg/kg) of a material which will kill 50% of a population of test animals. According to the US Dept. of Health (19), the LD_{50} values of both MDI and TDI (2,4-toluenedisocyanate) are 31,690 and 5,800 which are surprisingly non-toxic, compared to 317 for phenol, 800 for formaldehyde and 3,530 for acetic acid which are far more toxic. MDI has a vapour pressure of approximately 10^{-5} torr (mm Hg). The threshold for limit values for organic compounds are the values normally thought to be as the maximum exposure without unreasonable danger. Even though the threshold limit of MDI is low (0.05 ppm), the low vapour pressure makes this value relatively easy to maintain. Ball and Redmann reported that 0.01 ppm MDI is maintained with no difficulty under normal working conditions in a particleboard mill using no special precautions (9). Although the value for MDI is low, its vapour pressure is 10^{-5} mm Hg at room temperature, while for phenol formaldehyde, the vapour pressure is 10 mm Hg, or seven orders of magnitude greater. By inhalation, both TDI and MDI are extremely toxic (80 ppb and 130 ppb, respectively). However, especially in the case of MDI, its extremely low vapour pressure at room temperature greatly reduces the evaporation into the atmosphere. The use of MDI should be acceptable provided the formation of mist is controlled by good housekeeping,.

Hydrogen cyanide (HCN) is highly toxic; concentrations above about 280 ppm are immediately fatal. HCN is generated on burning all nitrogen-containing organic compounds. However, the actual amount present in the smoke varies widely depending on the oxygen level in the air (20). Ashida reported that plywood gave off about one-tenth the HCN of wool yarn and polyacrylonitride yarn and about twice as much HCN as various TDI foams (21). The HCN released by the combustion of isocyanate bonded particleboard or plywood is going to be overshadowed by both the wood and other materials in a fire situation and the hazard from HCN is not thought to be as important as that from CO in actual fires (20,21).

CONCLUSIONS

Isocyanate adhesives have been used in the reconstituted wood products industry for more than 20 years. In addition to particleboard, finger-jointing and laminated lumber, the use of isocyanates adhesives has been expanding to manufacture oriented strand board (OSB), waferboard, MDF, plywood and LVL. Considering the characteristics of the use of isocyanate adhesives such as fast-curing, better gluability, wider gluing conditions, formation of a wood/adhesive bond and elimination of formaldehyde release, isocyanate adhesives show promise as a future replacement for PF resins, although long term durability of isocyanates bonded gluelines is to be clarified. CSIRO Forestry and Forest Products has already commenced research on this new type of versatile wood adhesive.

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CURRENT RESEARCH ACTIVITIES ON WOOD ADHESIVES AT CSIRO

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ABSTRACT

The reconstitution of wood products offers a means of utilising more of the fibre from the worlds diminishing forest resources. However, these composite products are entirely dependent on the use of highly durable creep-resistant adhesives for the maintenance of full structural integrity under all exposure conditions.

At present the only proven adhesives that can meet these requirements are based on the condensation products of phenols and formaldehyde such as phenol-formaldehyde(PF), resorcinol-formaldehyde (RF), tannin-formaldehyde (TF) and their combinations.

A number of the shortcomings of these structural wood adhesives, such as relatively slow curing for PF's, large amounts of unreacted resorcinol resulting in poor bonding and environmental problems for RF's, and the lack of suitable crosslinking agents for radiata tannin adhesives are highlighted. Some of the current lines of research to overcome these problems at CSIRO are reviewed.

INTRODUCTION

The efficient use of forest resources is vital for environmental, ecological and commercial reasons as sources of large diameter high quality logs for sawn timber rapidly decrease. Suitable wood adhesives offer the means of utilising a far greater percentage of all forest resources producing a range of products such as panels, beams and a multitude of their combinations in sizes, strengths and with a uniformity that cannot be matched by sawn timber.

Over the period of 1994to1996(1), Australia produced approximately 1.5 million m^3 of composite products such as plywood, laminated veneer lumber (LVL) medium density fibreboard (MDF), particleboard and laminated beams. Adhesives presently used for these products are urea-formaldehyde (UF), melamine-urea-formaldehyde (MUF), phenol-formaldehyde (PF) tannin-formaldehyde (TF), resorcinol-formaldehyde (RF) and phenol-resorcinol-formaldehyde (PRF) costing Australian industry between A $80 - 100 million per year.

DURABILITY OF WOOD ADHESIVES

Adhesives may be grouped in accordance as to whether they are thermoset, thermoplastic or elastomeric in nature. Only thermoset adhesives such as PF, RF, TF, MF, MUF and UF can be considered as potential structural wood adhesives because of their creep resistance.

However, an important characteristic of adhesives is their chemical resistance to decomposition in their intended exposure environment. The most extensive literature on the durability of wood adhesives was published by Knight (2) of the Forest Products Laboratory, Princess Risborough, England. This original work dating from 1940 has been added to by other researchers such as Dinwoodie (3), and the experience of CSIRO shows that only phenolic type adhesives (PF, RF, TF etc) are acceptable for all weather, humidity, temperature and stressed-applications. This is something that must be considered in the "global market arena" and in the age of product failure litigation.

Phenolic type adhesives have one specific property that aminoplastic adhesives such UF and MUF do not have. It is their inability to be readily hydrolysed and broken down into their original constituents under the action of water, either in the liquid or vapour form. This property also solves the problem of in-service formaldehyde emission which aminoplastic adhesive bonded products can only control by the use of scavengers which are likely to further lower their durability. For these reasons the Wood Adhesives Group at CSIRO has concentrated much of its effort into further improving the properties of phenolic type adhesives.

PHENOLIC RESINS

Traditional phenolic resins are usually made by reacting phenol (1.0 mol) with formaldehyde (1.6-2.4 mol) in the presence of various alkali catalysts such as sodium or potassium hydroxide, alkali carbonates or alkaline earth hydroxides. The reaction is carried out under controlled temperatures until the resin reaches the desired end point viscosity, and then is cooled and shipped out. The final resin consists of phenolic nuclei linked together by methylene bridges to form phenol-formaldehyde polymers and formaldehyde attached to phenolic nuclei in the form of methylol groups. During hot pressing these methylol groups are converted into more methylene bridges between phenolic rings resulting in the formation of a very highly cross-linked thermoset polymer, which has negligible creep, cannot flow under further application of heat and is not hydrolysed by the action of water. These resins are, however, relatively slow curing and are less tolerant to bonding at higher wood moisture contents and to variations in tree species, compared with, for example, a MUF.

Various methods have been suggested and adopted in an effort to further improve the cure speed of PF resins, such as the use of carbonates and expensive resorcinol (4), esters and lactones (5), potassium hydroxide and carbonate (6), or simple addition of paraformaldehyde to the glue mix, high formaldehyde to phenol mole ratios and the addition of polyamines (7). Others have suggested the use of surfactants (8) in an effort to raise the wood moisture content tolerance and bondability. We at CSIRO have adopted a different approach.

CSIRO PHENOLIC RESINS

Since adopting the concept of "Molecular Designing" (9) in the early 1990's the Wood Adhesives Group now more than ever believes that molecular designing can deliver large improvements in phenolic resin performance. The first generation of commercialised resins have proven to have superior properties to traditional resins without resorting to the addition of curing accelerators. Preliminary results indicate that even better properties can be achieved. Extensive use of gel permeation chromatography (GPC) and nuclear magnetic resonance spectroscopy (NMR) during all stages of resin synthesis have confirmed that PF's can be designed with very enhanced properties. An example of their usefulness is in the production of LVL.

Hot-pressing time is a critical factor in the production of LVL, especially as thickness begins to exceed 45 mm.

Traditional PF adhesives require a glueline temperature slightly in excess of 100° C for several minutes for cure. With softwood the requirement is approximately 25 mins at 45 mm thickness, yet an increase of thickness to 63 mm requires approximately 45 minutes to achieve the required temperature. Our first generation molecular designed resin, which cures at a somewhat lower temperature, can reduce the hot press time of 63 mm LVL to approximately 40 mins. These same resins also have bonded a number of eucalypts species with excellent results whereas other commercial resins have performed poorly. Preliminary information now being obtained in the laboratory has indicated that a second generation of resins is likely to be even faster.

RESORCINOL ADHESIVES

Resorcinol (m-dihydroxybenzene) is a very reactive with formaldehyde and the expensive phenolic. Because of its high reactivity, it can be used in the room temperature curing of fully durable adhesives for the production of laminated beams, finger jointing and other "cold setting" structural applications. A resorcinol-formaldehyde (RF) resin is produced by reacting less than 1.0 mole (typically about 0.6-0.7) of formaldehyde with resorcinol. Higher formaldehyde ratios, greater than about 0.7, usually result in the resin gelling in the resin reactor. For curing purposes, the RF resin is mixed with a formaldehyde source such as paraformaldehyde and fillers, and used for laminating or finger jointing.

It has been the experience at CSIRO that RF resins perform poorly or erratically in finger jointing and that a very large percentage of finger joints do not achieve appreciable levels of fibre failure when tested. This is vital if the joint is to have any acceptable durability in service. Visual observations have been that the joint usually fails because of excessive penetration of the resin into the semi endgrain structure of the wood. Furthermore it has been identified through the use of GPC and NMR that commercial resins contain very large amounts of unreacted resorcinol (ca. 30%) which represents a wastage of very expensive resorcinol. This is difficult to remove from washdown water and tends to act as an unwanted resin "solvent" promoting excessive endgrain penetration.

By adopting the principles of "molecular designing" it has proven possible to more fully react resorcinol with formaldehyde and thereby reduce the level of free resorcinol in these resins to around 5%.

This has resulted in the production of a new generation of RF resins with a number of advantages such as:

1. Attainment of higher finger joint strength.

2. A large cost reduction, as resin solids can be reduced from the typical 55% to less than 40%.

3. Lower formaldehyde requirement for curing and consequently less hazard in use

4. More complete use of resorcinol, resulting in far less of the difficult to treat free resorcinol in washdown water and consequently less deleterious environmental effects

5. Easier production by the resin manufacturer.

The molecular weight distribution (MWD) (Fig. 1) as determined by GPC of a CSIRO resin (1) may be compared to that of a typical commercial RF (2) indicating that the commercial sample has much more unreacted resorcinol. Table 1 is representative of the results using three point bending tests (M.O.R.) of 65 mm wide by 32 mm thick finger jointed eucalypts hardwood, the joints being tested in the vertical position. Visual assessment of wood failure of the 20 mm long by 1.0 mm wide tips has also been included.

Further investigations of these resins for softwood finger jointing and as laminating resins is envisaged in the near future.

RADIATA TANNIN ADHESIVES

Since the early 1950's, bark extracts have been studied as potential wood adhesives (10). Later studies by Plomley (11) showed that extracts from black wattle (Acacia mearnsii) could be used for the production of waterproof adhesives. However, whilst this and further work by Plomley indicated that radiata bark extracts were also potentially attractive as waterproof adhesives, two major drawbacks compared with wattle tannin were also realised.

These related to the extreme and variable viscosities of high yielding radiata extracts, and the very fast reaction with formaldehyde donors such as paraformaldehyde or urea formaldehyde concentrates, which are the usual hardeners for wattle extracts.

Various methods have been used as a means of reducing the viscosity of radiata tannin extracts, the most usual being either extraction and or treatment of the extractives with sodium metabisulfite or sodium sulfite, either alone or in conjunction with other chemicals such as alkalis and carbonates (12). Whilst the sulfitation treatment of extracts did reduce the overall viscosity of extracts, gluing results using these extracts were variable to poor, and coupled with the lack of suitable slower reacting hardeners, only served to compound the problem.

Gluing veneer trials by the author, using either extracts that had been extracted with sulfite or the total extract treated with sulfite, indicated that a portion of the extract would overpenetrate the wood surface, resulting in excessive loss of glue solids. However, this was quite often coupled with a portion of a friable, non-flowed extract component left in the glueline. The overall result was most usually poor to variable bonding. Pioneering work by Yazaki and Hillis (13) clearly indicated that extracts had very wide molecular weight distributions, but perhaps more importantly, that sulfiting tended predominantly to attack the low molecular weight fractions of the extract. This resulted in an extract with lower viscosity, but one comprised of a very low molecular weight fraction that overpenetrated the wood interface, plus a largely unsulfited high molecular weight fraction that exhibited "no flow", the result still being poor to variable gluing results.

Largely for this reason it was decided to extract in stages (14), the first stages designed to remove the lower molecular weight fractions and subsequent stages removing the high molecular weight fractions, sulfiting only the high molecular weight fraction and then recombining with the unsulfited fractions. The result was a very marked improvement in gluability and a reduction in variability because of a narrower range molecular weight extract. This type of technology has been developed to the stage where industry has established a pilot plant (200 tonnes/year) to prove this technology with a view to its full commercialisation.

Various hardeners such as paraformaldehyde and urea formaldehyde concentrates have been used for crosslinking the very reactive radiata tannin extracts. Both hardeners are used with the far less reactive wattle extracts, the more usual being urea formaldehyde concentrates, because of its lower 'fume" level. Neither of these hardeners are really appropriate for radiata. Paraformaldehyde has been used but usually at pH's of between 4-6.

Radiata tannin is considerably less reactive as pH approaches 4.0 but it's solubility is much reduced. This may be linked with the need to add acids, with consequential salt formation, to reduce the pH of many extracts extracted under alkaline conditions.

When made using this method, bonded products such as particleboard tended to have variable strength properties and high levels of water uptake due to the presence of soluble salts. Urea formaldehyde concentrates cannot be used at lower pH's because of the likelihood of their selfcondensation.

Work at CSIRO Forestry and Forest Products has been focussed on the synthesis of a hardener suitable for radiata tannin, but without the drawbacks presented by existing hardeners. The result has been the development of a novel hardener having no salt problem whilst at the same time allowing a very long pot life at room temperature, yet staying very reactive during hot pressing. This work has resulted in a patent application.

The rate of condensation at pH 8.0 of this hardener with urea formaldehyde concentrates with a high yield extract (as measured by increase in viscosity at 25° C) clearly shows the enormous difference between these two systems (Fig.2).

Laboratory fabricated boards bonded completely with radiata tannin using this type of hardener has exhibited formaldehyde emissions of less than 0.5 mg per 100g of sample. This level of formaldehyde emission can be orders of magnitude less than other common adhesives presenly used.

CONCLUSIONS

Phenolic type adhesives are presently being developed that will further cement their place as the pre-eminent structural wood adhesives suitable for all environmental exposure conditions. This is especially important in the rapidly expanding "Global Market" where composites may now be expected to be shipped to the four corners of the world.

Fig. 1

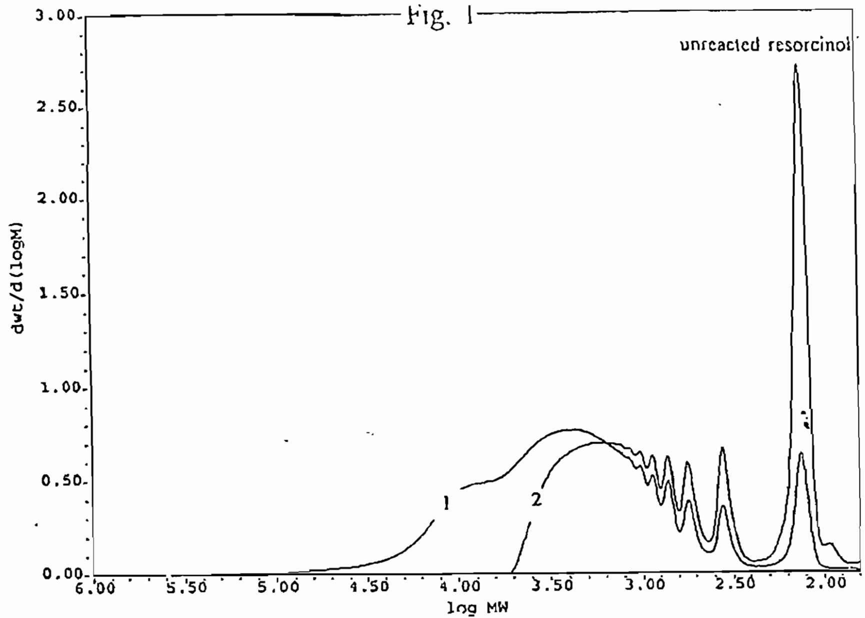


Table 1

RF	Parts/100 of Filler	Parts/100 of Para-formaldehyde	End Pressure (MPa)	Modulus of Rupture (MPa)	% Wood Failure
RF14	5 MSF	5.16	4.08	71.5	85
	5 WF		8.16	80.4	60
			12.24	71.5	30
RF15	7.5 MSF	5.16	4.08	62.5	100 RB
	2.5 WF		8.16	53.6	100 RB
			12.24	71.5	40
RF16	7.5 MSF	5.16	4.08	84.9	70
	2.5 WF		8.16	75.9	10
RF17	7.5 MSF	5.16	4.08	67.0	100 RB
	2.5 WF		8.16	71.5	RB

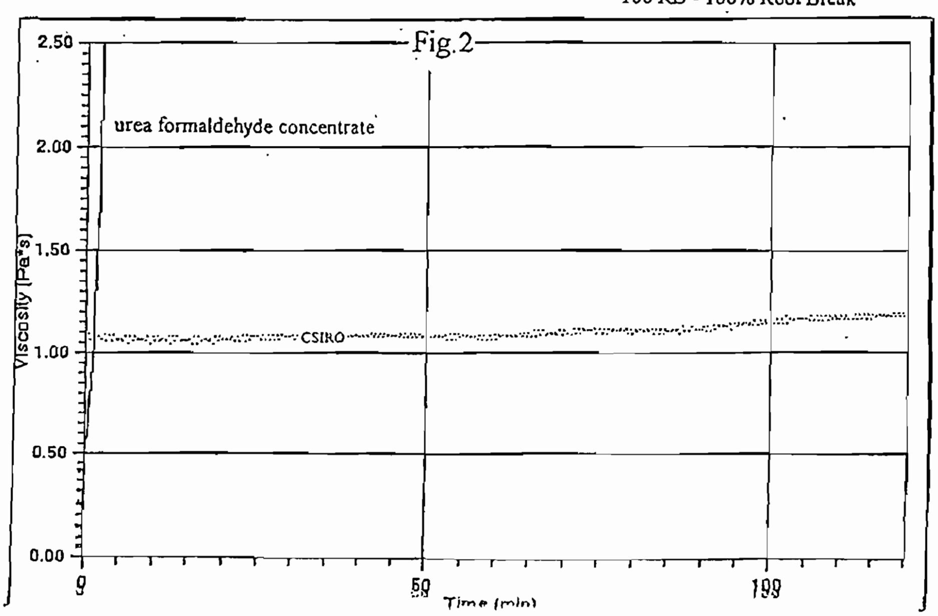
MSF = Macadamia nut Shell Flour

WF = Wood Flour

RB = Root Break

100 RB - 100% Root Break

Fig.2



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ADDING VALUE TO HARDWOOD CHIPS

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ABSTRACT

This study investigated the processing conditions required to convert young, small log, hardwood residues into reconstituted materials similar to those produced commercially from softwood residues. The materials were tested for their physical and mechanical properties and these properties were compared with those of softwood (*Pinus radiata*) products produced under identical laboratory conditions.

The initial results are not fully optimised but they indicate that the residues from sawing or thinning operations, for a range of young, small log, hardwood species, can provide a resource suitable for composite production. The composites display properties comparable to those required by the current Australian standards for particleboard and medium density fibreboard (MDF).

INTRODUCTION

The hardwood sawmilling industry converts waste material and thinnings to export woodchips for pulp production. In contrast, softwood sawmilling produces an integrated range of reconstituted products such as particleboard and MDF, as well as chips, to cope with its residual material.

Our aim is to add value to wood chips, or to thinnings from hardwood operations, by reconstitution. Fibres, sawdust, particles, flakes, veneers or small pieces of timber can be reconstituted into products such as panels and structural materials. These composite materials may be bound together with inorganic adhesive systems (eg. cement or plaster fibre/particle boards) or more traditional organic adhesive systems (eg. plywood, LVL, particleboards and MDF). The results of trials on young, small log, hardwood resource in existing processes are reported in this paper.

MATERIALS AND METHODS

Wood resources

17-year old *E.camaldulensis* and *E.grandis* trees from Lindemans, Karadoc, Victoria, irrigated with winery effluent, and 18-year old *E.saligna* trees from the Sunraysia Water Board, Victoria, irrigated with municipal effluent, were selected on the basis of their potential for sawlogs, and consequently tended to be the largest and straightest individuals on each site. Two trees were sampled to represent each species.

Two 15-year old *E.globulus* trees were sampled from a beef-cattle farm at Alexandra, Victoria. The trees were among a stand of other eucalypts planted at the bottom of a river valley where rapid growth was probably influenced by ready access to groundwater from a nearby stream.

Thinnings from a plantation of effluent-irrigated 6-year old *E.grandis* trees, grown at the Goulburn Valley Region Water Authority farm in Shepparton, Victoria, were harvested and debarked.

Preparation of woodchip samples

The selected trees from Karadoc and Alexandra were felled and the stems cut into one or more sawlogs of a minimum 250 mm small end diameter and a minimum length of 4.3 metres. The sawlogs were transported to the Timber Industry Training Centre sawmill located at Creswick, near Ballarat, Victoria. The logs were debarked and after sawing, the off-cuts collected to provide a representative sample of the sawmill residues. The off-cuts were chipped at the CSIRO Forest Products Laboratory, Clayton in a pilot-scale Bruks 980 M chipper (55-kW motor).

For the 6-year old *E.grandis* thinnings from Shepparton, one truck load was transported to Australian Forest Industries (AFI) in Myrtleford, Victoria. The logs were chipped at the mill and woodchip samples despatched to CSIRO Forest Products Laboratory.

The woodchips were mixed by the "cone and quarter" method to provide a uniform sample and subsequently screened in a Rotex vibratory screen. Accepts were collected from woodchips which passed through a 32 mm diameter hole screen and were retained on a 6 mm diameter hole screen. The woodchips were stored in polyethylene bags at 4°C prior to processing in the Sunds Defibrator CD300 pilot plant unit.

MDF fibre preparation

The pilot plant Defibrator is a single disc unit driven by a 105 kW motor running at 3000 r/min. It consists of a PREX (Pressure Expansion) screwfeeder which compresses the woodchips to aid fibre separation. The compression ratio is 1:4. After compaction, the woodchips are introduced into the lower part of the impregnation vessel housed within the preheater. Twin screws lift the macerated woodchips to the top of the impregnator as well as into the preheater. In the production of pulp from a chemical-free mechanical process, such as thermomechanical or medium density fibre production, woodchips are transported through the impregnator in the same way as described above but in an air rather than a liquid medium. The refiner has both disc (300 mm diameter) and conical (100 mm width) elements for refining, which can be independently adjusted for gap width. The system may be pressurised with steam to a maximum of 1.73 MPa (250°C).

Woodchips were atmospherically presteamed for about 20 minutes in the hopper of the CD300 pilot plant unit. The chips were then processed according to the conditions outlined in Table 1. Three separate trials at 164°C, 173°C and 180°C were performed on *E.globulus* to determine the optimum processing temperature to produce fibre for manufacture of the highest quality fibreboard. A temperature of 170°C was selected as the optimum and was used for all other eucalypt species for MDF fibre manufacture. Plate gaps and pressures were adjusted in an attempt to minimise fines from the various species.

Table 1 MDF fibre processing conditions

Species	Process temp. °C	Retention time min.	Press. 10^5 Pa	Plate gap flat	Plate gap cones
E.globulus (1)*	180	5	9.0	0.5	6.0
" (2)*	173	5	7.5	0.5	3.0
" (3)*	164	5	5.5	0.35	2.0
E.saligna	170	8	6.8	0.5	2.0
E.camaldulensis	170	8	6.8	0.5	2.0
E grandis (17 years)	170	7	6.8	0.4	2.0
E grandis (6 years)	170	4	6.8	0.4	2.0
P.radiata	180	5	8.8	0.2	2.0

*** 1, 2 and 3 denote the different preparation conditions for fibres used in MDF panels reported in Table 3**

Particle preparation

Particles suitable for laboratory particleboard production were prepared from the chips (after sampling) by passing them through a Bauer refiner using breaker plates, once at a plate gap of 2.50 mm and then twice at a gap of 0.13 mm. The material was dried at 105^0 C until the moisture content (MC) was reduced below 3%.

Panel production

The particleboards were made by spraying a weighed quantity of dried particles with experimental phenol/formaldehyde adhesive (in a laboratory paddle mixer) to obtain a final resin loading of 8 % by weight. Allowances were made for the MC of the particles and the water content of the adhesive formulation (spray time was between 2.5-4.5 minutes). The resinated particles were weighed and preformed for pressing into panels within a pre-determined density range.

The pressing temperature was 185°C and a constant press cycle was maintained for all products using a 400 tonne, steam-heated, Windsor hydraulic press. The pressing cycle was to stops, using 18 mm spacer bars, over 30 seconds. The pressure was released in stages to allow de-gassing. The total time for the cycle was about 8 minutes.

The hot panels were block stacked in an insulated box and cooled overnight for at least 16 hours. The cooled panels were trimmed to remove edge effects then cut accurately to size, measured, weighed, and the density calculated (see Table 2). The boards were sanded on both sides after density measurements.

The MDF products were made from dried fibre which had been resinated with an experimental phenol/formaldehyde adhesive in a laboratory "blow line" at 8 % resin loading. No wax additions were made to the adhesive formulation. The resinated fibres were formed into a preformed mat and pressed at 185°C. A typical pressing cycle comprised a total time of 6 minutes. The spacer bars were 12 mm thick.

The hot MDF panels were block-stacked, cooled, densities were calculated, then the samples were trimmed and sanded before being tested (see Table 3).

RESULTS AND DISCUSSION

Particleboards

Particleboards were produced from *E. globulus, E. grandis* (17 year old), *E saligna* and *E. camaldulensis.* The actual particles varied in size and shape from those used commercially due to the non-availability of equipment. All products were prepared by a constant method. The adhesive system used was prepared from an experimental resin developed by CSIRO, Forestry and Forest Products and was considered generally suitable for a wide range of Australian hardwood species.

The processing conditions of time, pressure and temperature were similar to those used by the softwood panel industry and thus represented a feasible process for the commercial production of a hardwood product range in the future. However, in order to have a meaningful comparison, the samples were made to similar values of density and thickness, by pressing to stops using a calculated weight of wood particles. This procedure almost certainly results in panels which do not indicate the best performance of the hardwood resource, as one might expect the more dense hardwoods to generate stiffer and stronger panels with higher values of density.

The mechanical and physical properties of the experimental hardwood particleboards are reported in Table 2. The elastic modulus (MOE) [stiffness] and modulus of rupture (MOR) [bending strength] of the materials (except for *E. saligna*) compare well with the softwood control and exceed the requirements of the standard.

The lower values for *E. saligna* would appear not to be due to poor bonding as the internal bond value of 1300 kPa is greater than *E. globulus* (1050 kPa), which has acceptable values of MOE and MOR. As both the values of density and fracture toughness (FT) [an indication of the ability to absorb impact] are low in the case of *E. saligna* (see Table 2) it could be suggested that the density profile is such that the density at the face of the panel is low and hence fails in bending due to lack of strength in the tensile face under load. Greater compression during processing could increase the density and assist in overcoming this lower performance.

Table 2. Properties of laboratory particleboards

SAMPLE	MOE (GPa)	MOR (MPa)	FT (kJ/m^2)	IB (kPa)	Density (kg/m^3)	24 hr. Soak (% swell)	1 hr. Soak (% swell)
E. globulus	2.9±0.3	21.2±2.3	4.4±0.3	1050	746	20	4.1
E. grandis (17y)	2.9±0.1	21.3±0.7	4.4±0.2	1460	754	17	3.8
E. saligna	2.7±0.3	18.4±3.0	3.5±0.6	1300	733	20	4.0
E. camaldulensis	2.9±0.1	23.1±1.2	4.3±0.3	1400	750	18	3.9
Control (*P. radiata*)	3.2±0.4	21.3±2.9	3.6±1.2	1400	754	26	16
Standard *	2.5	16	-	400	763	12	12

* AS/NZS 1859.1 (INT): 1995

At a similar density of approximately 750 kg/m^3, the softwood control shows much greater uptake of water (16 % swell) after a 1 hour soak compared to approximately 4% for all the panels made from hardwood species. After 24 hours soaking in water the values are approximately 26 % for softwood and 20 % or less for the hardwood panels. Increasing the density of the hardwood panels may reduce the 24 hour soak values even further. No water repellent additives were added to the experimental panels so direct comparison with commercial standards has little significance with respect to soak tests.

Medium Density Fibreboards

MDF panels were prepared from *E. globulus, E. saligna, E. camaldulensis and E.grandis* (aged 17 and 6 years) and their properties compared with the requirements of Australian standards.

The equipment used has been described in the section "**MDF fibre preparation**". A range of *E. globulus* fibres were prepared using different processing conditions in an attempt to optimise the fibre properties for preparation of MDF panels.

Table 3 contains the mechanical and physical properties of the laboratory hardwood MDF panels.

The three different sets of processing conditions used to prepare the *E. globulus* fibre resulted in little change in the panel performance of the resulting composites. The *E globulus* appears to be somewhat stiffer and stronger (see Table 3) than the other species tested.

Table 3 Properties of Laboratory MDFs

SAMPLE	MOE (GPa)	MOR (MPa)	FT (kJ/m^2)	IB (kPa)	Density (kg/m^3)	24 hr. Soak (% swell)	1 hr. Boil (% swell)
E. globulus 1*	3.6±0.1	37.0±2.8	6.0±0.6	200-300	760	15	25
E. globulus 2*	3.9±0.4	39.0±3.7	6.9±0.7	"	768	17	28
E. globulus 3*	3.5±0.4	40.0±1.8	8.0±0.2	"	770	18	30
E. saligna	3.2±0.3	33.9±2.8	6.6±0.5	250	765	19	34
E. camaldulensis	3.2±0.2	35.6±3.6	7.5±1.1	300	775	17	31
E. grandis (17y)	3.1±0.3	32.9±4.2	6.7±0.6	200	760	20	40
E. grandis (6y)	3.3±0.3	36.2±3.4	8.7±2.6	320	740	20	34
Standard *	2.8	30	-	600		12	-

AS/NZS 1859.2 (INT) : 1995
* See Table 1.

One surprising feature, which requires re-examining, is the fact that the internal bond strengths (IB) of the hardwood products are very low compared to that required by Australian Standards, yet the MOE and MOR appear more than adequate to meet such standards.

CONCLUSIONS

Residual material from young, small diameter hardwood may be converted into reconstituted products using existing commercial processes.

The mechanical properties of the reconstituted hardwood products exceed the requirements of MOE and MOR for the Australian Standards. This result indicates an opportunity to add value to a resource currently exported as woodchip.

Further consideration needs to be given to these resources in order to optimise their performance and maximise their value within Australia - before they are considered for export as wood chips for overseas pulp production.

THE USE OF MODELLING TO PREDICT WOOD AND LOG PROPERTIES

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ABSTRACT

Wood properties have an important impact on the suitability of logs for a range of uses: solid wood; engineered wood products; pulp and paper. Advances in tree breeding and silviculture have brought about the possibility of growing radiata pine trees to large dimensions in as short a time as 20 years. The predominance of juvenile wood in the central portion of the stem (about 10 rings from the pith) may limit the suitability of such logs for some high value uses. The development of models to predict wood characteristics of plantations from different geographic regions, grown under specified silvicultural regimes, will assist in planning the allocation of logs to different processes.

INTRODUCTION

The commercial plantation estate of New Zealand is currently 1.5 million ha of plantation forests (5% of the land area), and expanding at an average rate of about 70,000 ha/annum. 90% of the plantation forest area is in one species, *Pinus radiata* D.Don, with an average growth rate in excess 20 m^3/ha/annum. This allows sawlog rotations of between 25 and 35 years. Harvested volumes are projected to double from the current level of 16 million m^3 within 15 years due to the high proportion of young plantations (*NZ Forest Owners Association, 1996*).

The consequences of this situation are:

(1) Much of the resource is still quite young;
(2) Wood properties and log quality have also changed.

In recent years, tree breeding programs internationally have concentrated on increasing stem volume production through genetic selection for height and diameter growth (*Zobel and Talbert, 1984*). With the steadily increasing proportion of improved and intensively managed plantations, and a move in forest management to shorter rotations, wood and fibre quality will become one of major concerns in forest products industry throughout the world (*Bendtsen 1978*). The ability of conventional growth models to yield information on wood quality is quite limited, being restricted to the indirect relationships between stem size, age and wood properties. There is a need to combine the data collected in wood quality surveys (*Cown et al. 1991*) with stem growth information.

Since 1994, a suite of models of wood properties has been under construction to document the patterns of variation of wood properties within trees (*Tian and Cown, 1995 and 1996a; Tian et al. 1994, 1995*). A computer package (**WoodPro**) has been developed to predict and simulate the variation of important wood properties (wood density, tracheid length, spiral grain, heartwood) in radiata pine in relation to geographic location.

The present project focuses on the development of a computer simulation model (**STANDQUA**) to document the interaction of major wood properties with site potential, silvicultural regime, and stem growth. The objective is to develop a new generation tool to assist in plantation management (Fig 1).

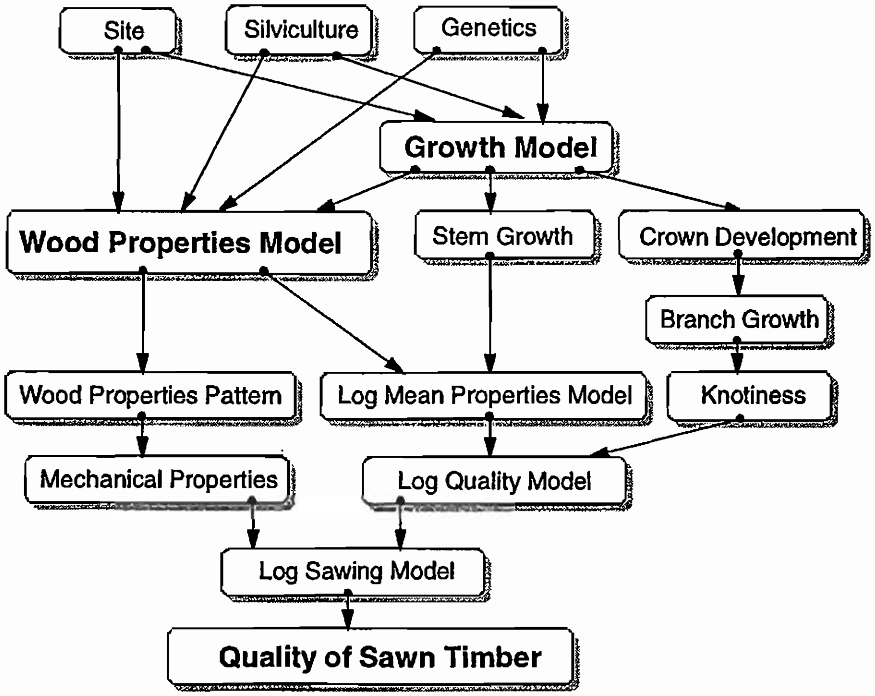


Fig 1: General framework linking the wood properties model to silviculture, site and tree growth. Note: some links have not been fully developed yet.

LINKING WOOD PROPERTIES MODELS TO TREE GROWTH

Ring Width Model

In order to link wood properties models with growth models, a general model of annual ring width is nessecery. Ring width data used to develop this model were obtained from previous studies carried out in New Zealand.

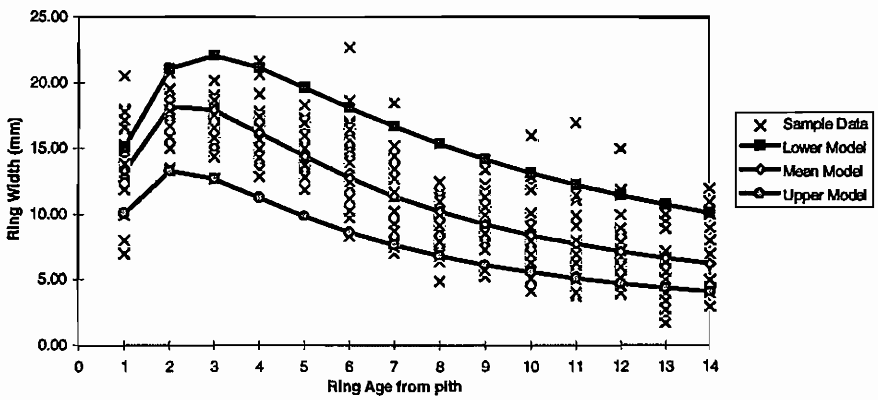


Fig 2: Comparison between measured data and model about the effect of ring age on the ring width.

According to the results of statistical analyses, the model accurately simulated the variational pattern of the effect of ring age on the ring width in radiata pine. This model was selected to link with tree taper functions to simulate tree profiles using computer simulation. Fig 2 illustrates the well-known proportional relationship between ring age and ring width from one study.

Stand Basal Area Growth (Increment)

Stand basal area growth (increment) of radiata pine thinned to varying densities is predicted according to Whyte's and Woollons's model (*Whyte and Woollons, 1990*). A new model was constructed from analyses of growth and yield data (Fig 3).

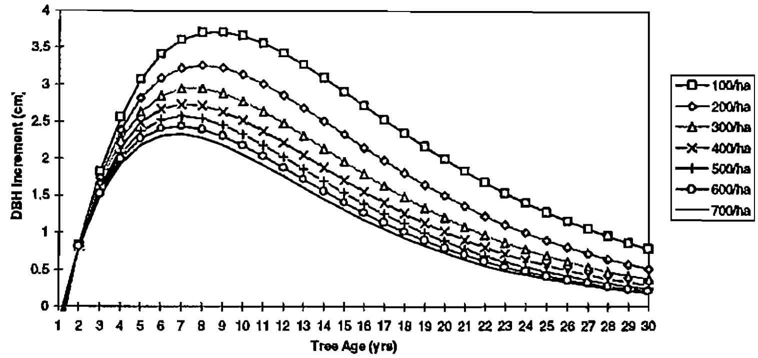


Fig 3 : A model for annual DBH increment at different stockings.

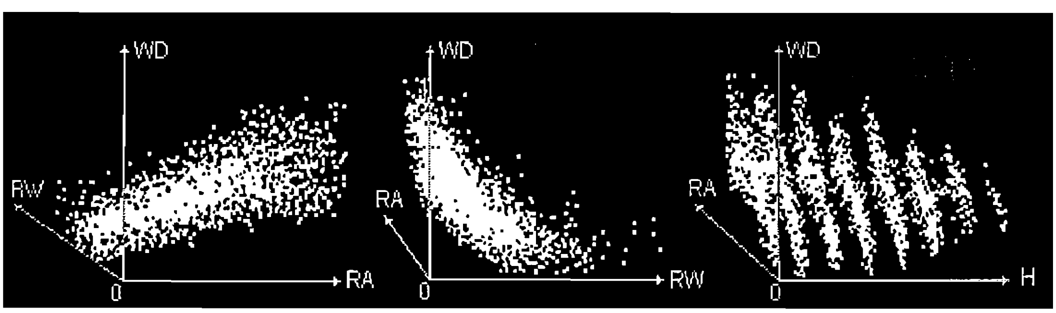
Height Growth Model

Height growth depends on site quality and genotype. Site index equations for radiata pine in New Zealand were applied to estimate stand height on different sites (*Burkhart and Tennent 1977; Eyles; 1986*). The height growth model was derived in this way.

Taper Equations

Stem profile was modelled using the polynomial taper equation that was adapted from Goulding and Murray (1976) and Gordon (1983).

MODELLING TREE GROWTH AND WOOD PROPERTIES



(a) (b) (c)

Fig 4: The variation of wood density (WD) versus ring number from the pith (RA), growth ring width (RW) and height in the tree (H).

Tree growth rate is directly affected by silvicultural regime and site (*Burkhart and Tennent 1977, West et al. 1982*). Many studies have indicated that both site and tree growth rate also have significant effects on important wood properties, such as wood basic density and tracheid length (*Harris, 1965; Grant 1977, Cown and McConchie 1981; Cown et al. 1991, Tian et al. 1996a and 1996b*). Therefore site, silviculture and tree growth can have both direct or indirect effects on the main wood properties.

Modelling Within-Tree Patterns Of Wood Basic Density

The model focuses on variables that affect wood basic density through their influence or dependence on stem growth. Three well-known variables were included: growth ring width, ring age and height in the tree stem.

In Fig 4 the data were plotted in 3-D mode to illustrate the variation of wood density with ring age from the pith, growth ring width and height in the tree. Fig 4(a) illustrates the well-known relationship between the density and ring age in radiata pine. Fig 4(b) quantifies the negative relationship between density and ring width. Fig 4(c) shows an overall tendency to a negative relationship between the density and height. Non-linear multivariate regression methods were applied in processing the sample data to build the model of the following form (*Bates and Watts 1988; Tian et al. 1996b*):

$$WD = k_1 + \frac{k_2}{RW} + k_3 \cdot RA - k_4 \cdot H$$

Where WD is wood basic density (kg/m3); RW is the growth ring width (mm); RA is the ring age; H is tree height level (m); k_1=329.567, k_2=116.243.567, k_3=6.299, k_4=0.347.

The main results of the statistical analysis for this model are shown in Table 1.

Table 1: Statistical analysis for wood density (WD)

Source	Sum of Squares	D.F.	Mean Square
Regression	.441076E+09	4	.110269E+09
Residual	5654077.314	2466	2292.813
Total	.446730E+09	2470	
Corrected	.118787E+08	2469	
Raw R-Squared (1-Residual/Total) = 0.987			
Corrected R-Squared (1-Residual/Corrected) = 0.528			

The residuals, when represented versus ring age, ring width, and height in the stem are randomly distributed and unbiased (Fig 5, Fig 6 and Fig 7) indicating that the regression coefficients are highly significant.

Ring age, ring width and height in the stem were used to predict wood density in the model. Rinag age played a positive role while both ring width and tree height were found to be strongly negatively related to wood density.

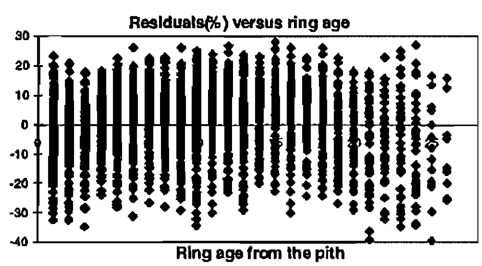


Fig 5: Residuals between the measured and predicted wood density (%) versus ring age

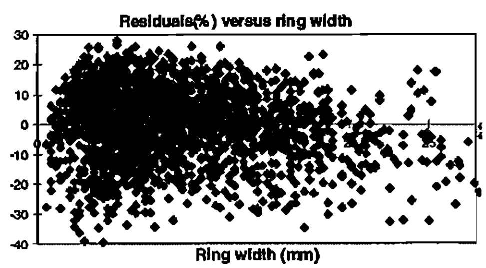


Fig 6: Residuals between the measured and predicted wood density (%) versus ring width

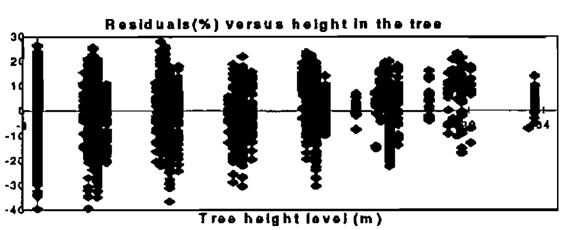


Fig 7: Residuals between the measured and predicted wood density (%) versus tree height in the tree

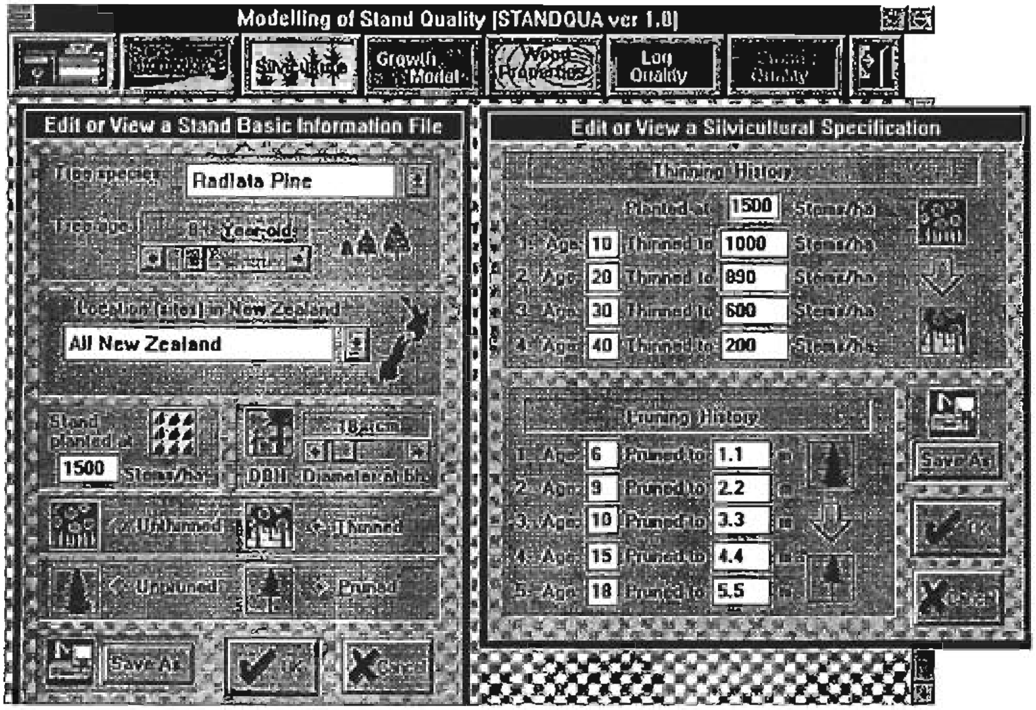


Fig 8: Software - StandQua interface

MODELLING THE EFFECT OF SITE ON WOOD PROPERTIES

Modelling The Effect Of Site On Basic Density

The environment has a strong effect on wood density in New Zealand. Research has demonstrated that average mean annual temperature is the main influencing factor, together with contributions from other site factors such as latitude, rainfall and soil nutrient status (*Harris, 1965; Cown et al. 1991*).

Regional breast height mean wood density models based on several hundred sites are shown in Table 2 (*Tian, Cown and McConchie 1995*).

TABLE 2: Regional wood density models:

Model	$WD = \dfrac{l_0}{1 + l_1 \cdot \exp(l_2 \cdot RA)}$		
Regions	l_0	l_1	l_2
Auckland	515.62	0.80	-0.15
Nelson	487.46	0.50	-0.11
Rotorua	484.78	0.57	-0.12
Wellington	457.37	0.44	-0.11
Westland	465.50	0.45	-0.11
Canterbury	452.14	0.43	-0.13
Southland	459.53	0.44	-0.08

Where WD symbolises wood densities, RA the ring age from the pith; l_0, l_1 and l_2, model parameters.

Modelling The Effect Of Site On Tracheid Length

In radiata pine, variation in tracheid length has been related to ring number from the pith, height above ground, geographic region and rate of growth (*Harris, 1965; Cown et al. 1991*).

Tracheid length models, relating tree age, ring number from the pith and tree height for different regions in New Zealand, have also been created by using multivariate non-linear regression (*Tian and Cown 1996b*).

APPLICATIONS

Comparison Of Silvicultural Regimes

The above models are incorporated in a software package (**STANDQUA**) which is used to predict the effect of site and silviculture on wood properties and tree growth of radiata pine plantations. It was developed specifically for use on personal computers operating under Microsoft Windows 3.1 or 95. This package can be run by non-specialists and enables users to simulate and compare the performance of stands which differ according to site index, silvicultural regime or tree age (Fig 8).

As an illustration, two theoretical stands having the same site index but managed under two different silvicultural regimes were simulated using **STANDQUA** (Table 3).

TABLE 3: Contrasting silvicultural regimes (examples only)

Tree Age	Stocking (Stems/ha)	
	Traditional Silviculture - Untended (Estimated Tree Nos.)	Modern Silviculture - Regular Thinning
0 (Planted)	3000	1500
10	2980	400
15	2960	250
28	790	248
30	730 (Felled)	245 (Felled)

Fig 9 provides general information about the size, stem taper and internal structure of the simulated average tree for the two silvicultural regimes respectively. **STANDQUA** predicted that the average tree of the untended stand is smaller with less taper than that of the managed (thinned) stand.

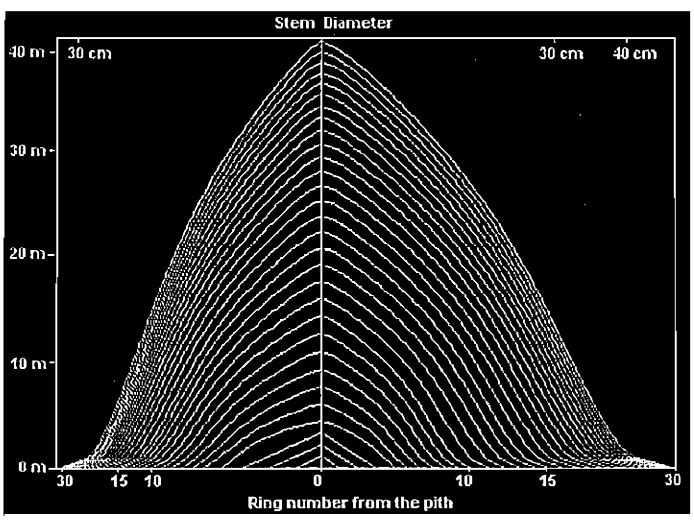


Fig 9: StandQua output (growth patterns) for two different silvicultural regimes on the same site index (28) in Rotorua at tree age = 30 yrs. Left: unthinned; right: thinned (see Table 3).

Fig 10 shows the general pattern of wood density variation in these two simulated silvicultural regimes. As expected, **STANDQUA** indicated that the pattern of the untended stand is a gently sloping rise with the increasing distance from the pith, and in contrast, the thinned stand shows a slight temporary decrease in density after each thinning. The other wood properties can be similarly compared visually or in tabular form.

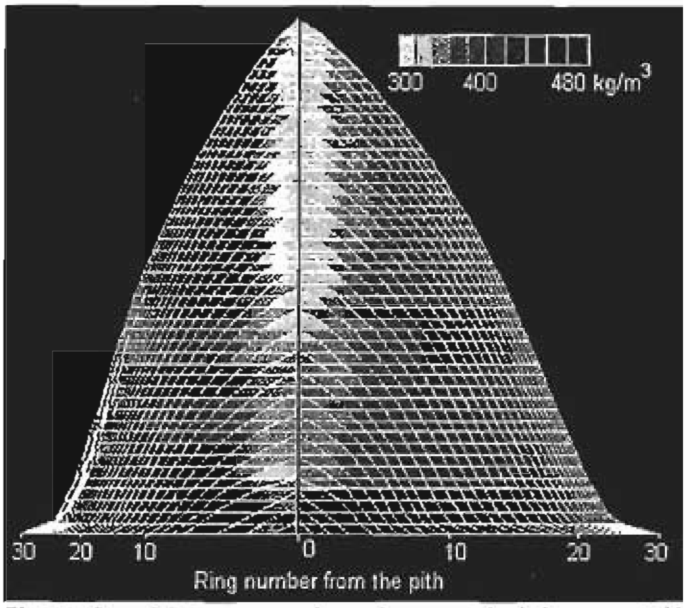
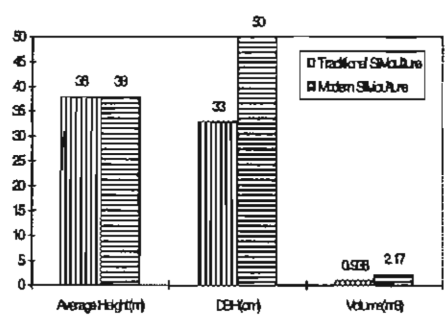
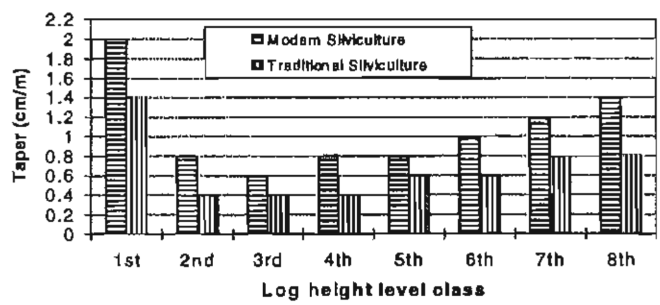


Fig 10: StandQua output (wood properties) for two different silvicultural regimes on the same site index (28) in Rotorua at tree age = 30 yrs. Left: unthinned; right: thinned (see Table 3).

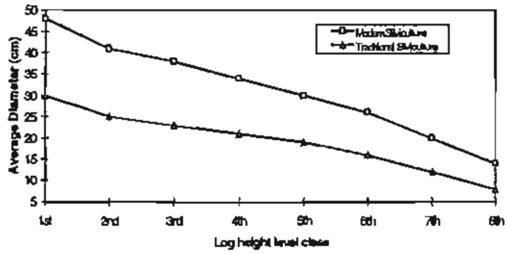
STANDQUA can provide a flexible basis for integrating further information on the relationships between tree growth and wood properties. Users can compare forest management practices and their affect wood properties. The result of comparing between two qualities from different silvicultural regimes using Table 3 were shown in Fig 11.



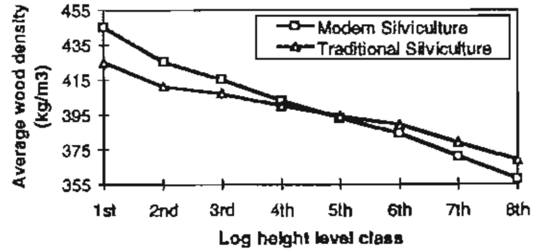
(a) Average Tree Height, DBH and Volume



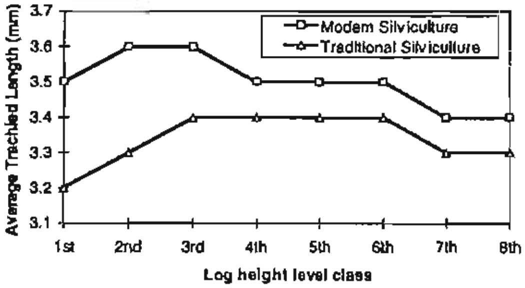
(b) Taper of stem



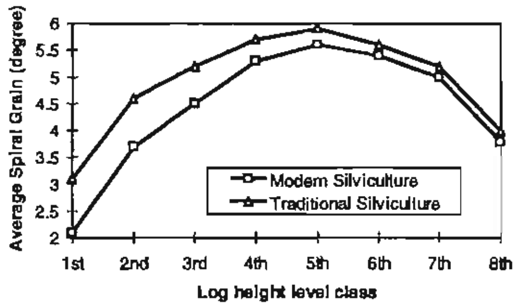
(c) Log Diameter



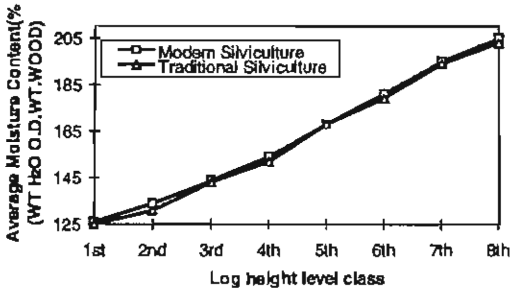
(d) Log Wood Density



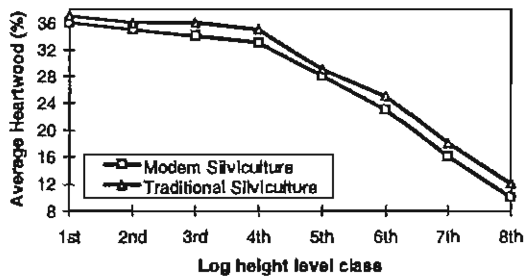
(e) Log Trachied Length



(f) Log Spiral Grain



(g) Log Moisture Content

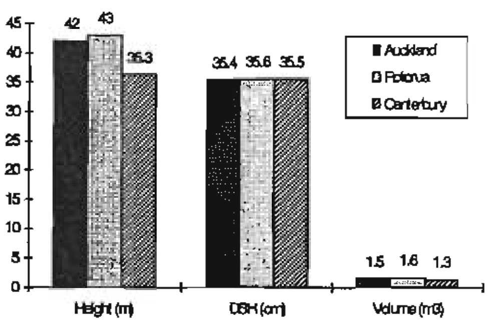


(h) Log Heartwood

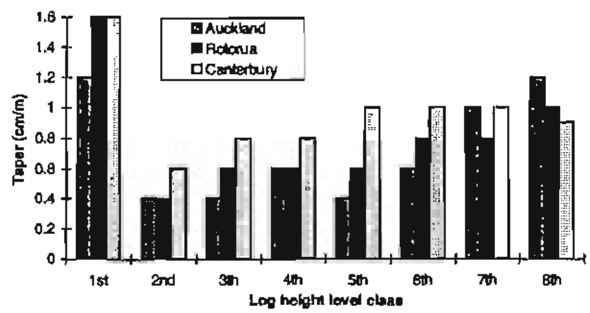
Fig 11: Comparison between two qualities from different silvicultural regimes.

Comparison Of Sites

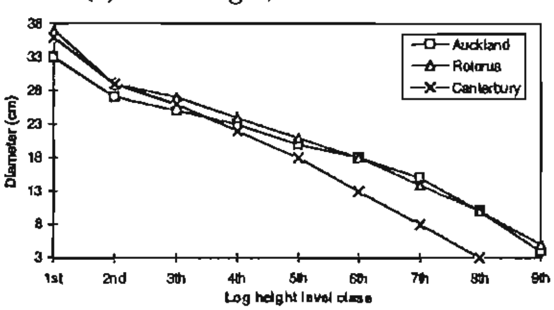
The same set of models can be used to compare the effects of site, using geographic data already collected (Fig 12).



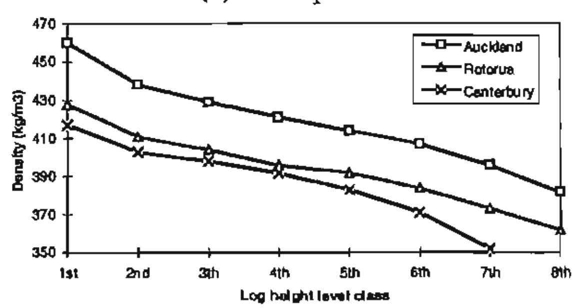
(a) Tree Height, DBH and Volume



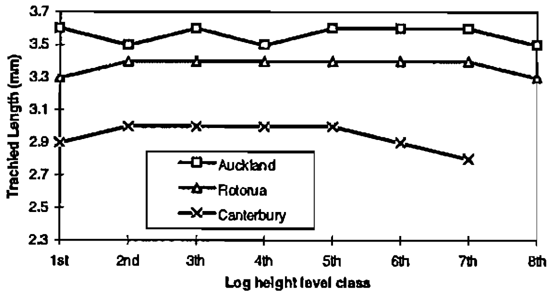
(b) the Taper of stem



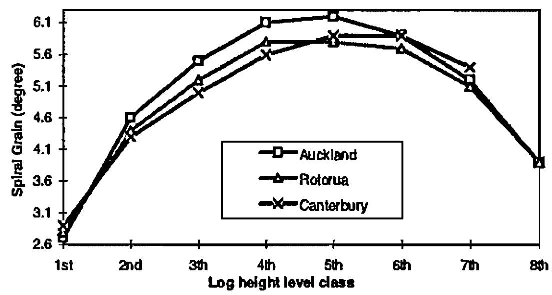
(c) Log Diameter



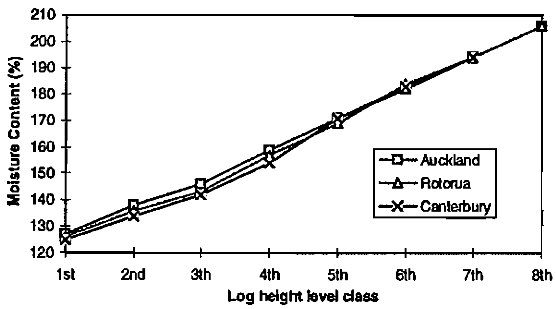
(d) Log Wood Density



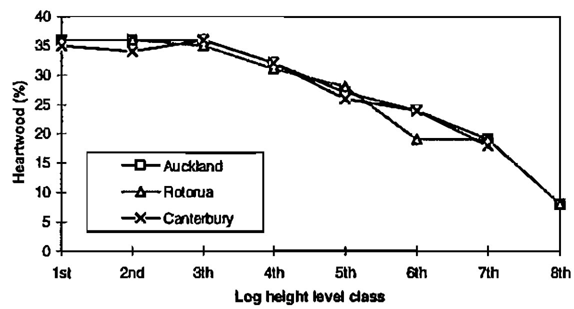
(e) Log Trachied Length



(f) Log Spiral Grain



(g) Log Moisture Content



(h) Log Heartwood

Fig 12: Comparison of qualities from three different sites.

Assessment Of Log Quality

Another application of **STANDQUA** is the assessment of log quality (e.g. wood density) of existing plantations either at the regional or the stand level. This application incorporates an algorithm to enable tree and log densities to be estimated from samples collected non-destructively from the breast height position (1.4m).

DISCUSSION AND CONCLUSION

Recent Wood Quality research at FRI has focused on the amalgamation of radiata pine growth and wood property data so that the development of plantations can be modelled in terms of important quality variables in addition to the traditional tree diameter and stem form. So far, a small number of wood properties have been successfully integrated into regional growth models. The next challenge is to incorporate branching characteristics.

ACKNOWLEDGMENTS

The authors wish to thank John Roper and Andy Gordon for their valued opinions and help.

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Wood quality and quantitative genetics of *Pinus radiata*

IV. Time trends in the genetic control of density and pulp and paper-making fibre traits and their interrelationships

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Abstract

Life-history studies of genetic and environmental variance components in a four-parent, radiata pine diallel revealed that genetic control over fibre (ie tracheid) wall thickness and ring density was extremely poor before crown closure (age 8-9 years). During this period, environmental variance (ENV) was extremely high, non-additive variance (NADV) and additive variance (ADV) were low. In contrast, the corresponding period of high environmental influence was much shorter lived and NADV was not significant for fibre size or fibre coarseness, which allowed ADV for fibre size to stabilise by age 5-6 years. ADV of ring density, fibre wall thickness and specific surface area improved only after crown closure when ENV had decreased significantly. By age 14-15 years ENV was still high (50-70 % of total variance) for fibre wall thickness, specific surface area and coarseness compared with that for fibre size and ring density (30 %).

Analysis of age-related changes revealed that parental breeding values for 80055 were lowest for ring density, highest for fibre perimeter and coarseness in the experiment. The range and coefficient of variation for ring density for wood with 80055 as a parent were half those of the densest wood (12197 family) but the range of fibre perimeter in wood of family 80055 was about three times that of family 12197. Ranks for parental breeding values for density, fibre wall thickness and fibre coarseness did not change with age after crown closure. Fibre specific surface area and fibre thickness were inversely related while fibre perimeter and coarseness, and fibre wall thickness and density were directly related.

Interrelationships between pairs of traits varied with time and genotype in this experiment. Most unexpectedly, interrelationships in progeny of parent 80055 differed from those of the other three parents over the same period. For example, after crown closure fibre coarseness was positively related to fibre perimeter and not to fibre wall thickness only for progeny of parent 80055. These results confirm the complex dependence of fibre coarseness on fibre size and wall thickness (Seth, 1990; Paavilainen, 1993) and suggest a temporal and genotype dependence.

Selection efficiency was high in all traits after crown closure when it was sometimes even in excess of 100 % due to higher heritabilities at ages younger than at 15 years.

Keywords

Pinus radiata, X-ray densitometry, fibre cross sectional dimensions, specific surface area and coarseness, heritability, variance components, age-age correlations, selection efficiency

Introduction

The economic importance of density as a reliable, easy to measure trait that closely regulates the suitability of wood for various end-products is universally acknowledged. Numerous studies have shown that density is a highly heritability trait and excellent reviews have been provided by Goggans (1961), Einspahr (1972), Zobel and Jett (1995) and Timell (1986). However, few studies have investigated age-related changes in heredity or variance components. The few available studies on age-age correlation of density are conflicting. Some suggest that the density of juvenile wood does not accurately reflect that of mature wood. For example, in their literature review Gonzales and Richards (1988) found that density in the initial 15 growth rings (juvenile wood) was unstable in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Yet, other studies in the same species (Vargas-Hernandez and Adams, 1992) and in loblolly pine (*Pinus taeda* L.) (Williams and Megraw, 1994) have contradicted this view.

The apparent contradiction in the literature could be attributed to a number of factors. Firstly, the terms "juvenile wood" and "mature wood" are used ambiguously in the literature. In contrast, the literature clearly suggests that the transition age from juvenile to mature wood varies between- and within-species (Loo *et al.*, 1985; Szymanski *et al.*, 1991; Zobel and Jett, 1995). It is therefore conceivable that mature wood density could be predicted reliably from juvenile wood density in species with an early transition age (eg. 7 years in loblolly pine) but not in another with a late transition age (eg. 10 to 14 years in Carribean pine (*Pinus caribaea* Morelet)) (Zobel and Jett, 1995). Another probable cause of the inconsistency in the literature and perhaps the most serious is the absence of standard sampling procedures (eg. sampling height, number of radii per tree, number of trees per family, number of families per progeny test and number of test sites), sample preparation (eg. extraction and conditioning), scanning and reporting. Smith (1966) expressed a similar concern and advocated standard experimental procedures.

No published report has been found on age to age changes in the variance components of fibre cross sectional dimensions (wall thickness and diameter). The two traits are important in pulpwood quality because of their large influence on both density and fibre coarseness. This scarcity of published reports was probably best explained over three decades ago by Goggans (1961) as "the reason is plain to see for the measurements are difficult and extremely tedious to make." Other researchers have echoed the same view (van Buijtenen, 1964; Green, 1965; Phillips, 1965; Paavilainen, 1993).

The purpose of this paper is to report on the life-history and variation patterns in the genetic parameters and structures of pulp and paper-making traits (ring density, fibre perimeter, wall thickness coarseness and specific surface area) in a small unthinned, 4 x 4 radiata pine diallel. Age-related changes in the relationships between breeding values of these traits are also reported.

Materials and methods

Wood samples used for this study were harvested from a 23 year-old radiata pine diallel cross (ie all possible combinations, in this case omitting selfs but including reciprocals) involving four parents; 80055, 12038, 12197 and 12447 (Nyakuengama *et al.*, 1996 a, b, c). Samples were prepared for Silviscan 1 and traits were measured following the method of Evans (1994 and 1995). In addition, fibre specific surface (S) was derived as follows:

$$S = \left(\frac{1}{T_w * \partial_w} \right)$$

where: ∂_w *is wall density (constant) and* T_w *is wall thickness*

The last eight individual growth-rings near the bark in trees of some families were too narrow to be accurately resolved (especially for maximum latewood density and minimum fibre radial diameter) and so they were omitted from this study. Moving-averages of pulp and paper-making traits in the initial 15 individual growth rings (corewood) in increment cores were analysed using a diallel least square analysis of variance and covariance in which all effects are treated as random using the DIALL computer program (Schaffer and Usanis, 1969). This program carries out a combining ability analysis (GCA) as in Griffing (1956) and extended to calculate parental breeding values (PBV) from general combining ability effects as follows: PBV = 2*GCA + experimental mean. In order to study age-related changes in the genetic structure of the traits, phenotypic variances were partitioned into environmental, additive and nonadditive genetic components as in Matheson *et al.* (1994). Selection efficiencies in all traits were calculated following the method of Williams and Megraw (1994); $E = [h_j r_{aj.m}/h_m]*100$ %, where: h_j is the heritability for juvenile trait, $r_{aj.m}$ is the juvenile-mature correlation of genetic additive variance and h_m is the heritability for mature trait.

Results and discussion

Fibre perimeter

Additive variance (ADV) in fibre perimeter was initially low but increased rapidly and linearly to a stable level which accounted for 80 % of the total variance by age 5-6 years (Fig. 1). These age-related changes were reciprocated in environmental variance (ENV), except in the opposite direction. Non additive variance (NADV) was initially low (≤ 5 % of total variance) and it remained insignificant through out the life of the experiment. Therefore ADV and ENV were the only important genetic determinants of fibre perimeter.

Two droughts which occurred at ages 8-9 and 10-11 years caused a 10 % increase in ENV and a concomitant decrease in ADV of the same magnitude. The effects of the second drought were only evident a growth season later (Fig. 1).

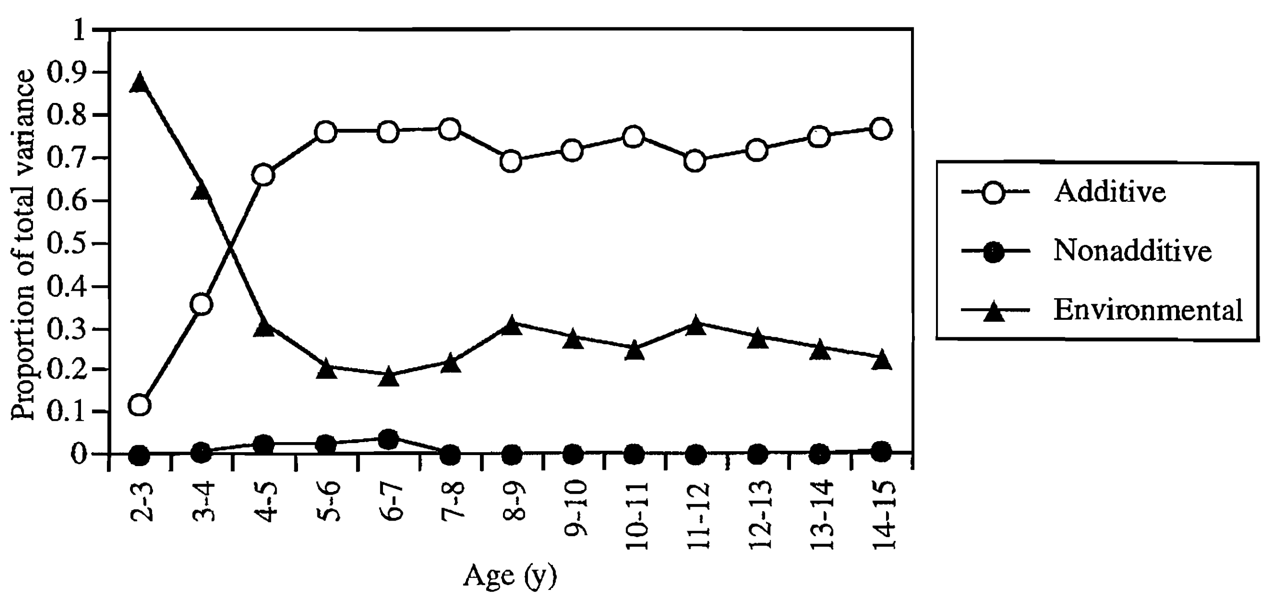

Fig. 1: Radial sequence of variance components in the fibre perimeter in breast-height increment cores of radiata pine.

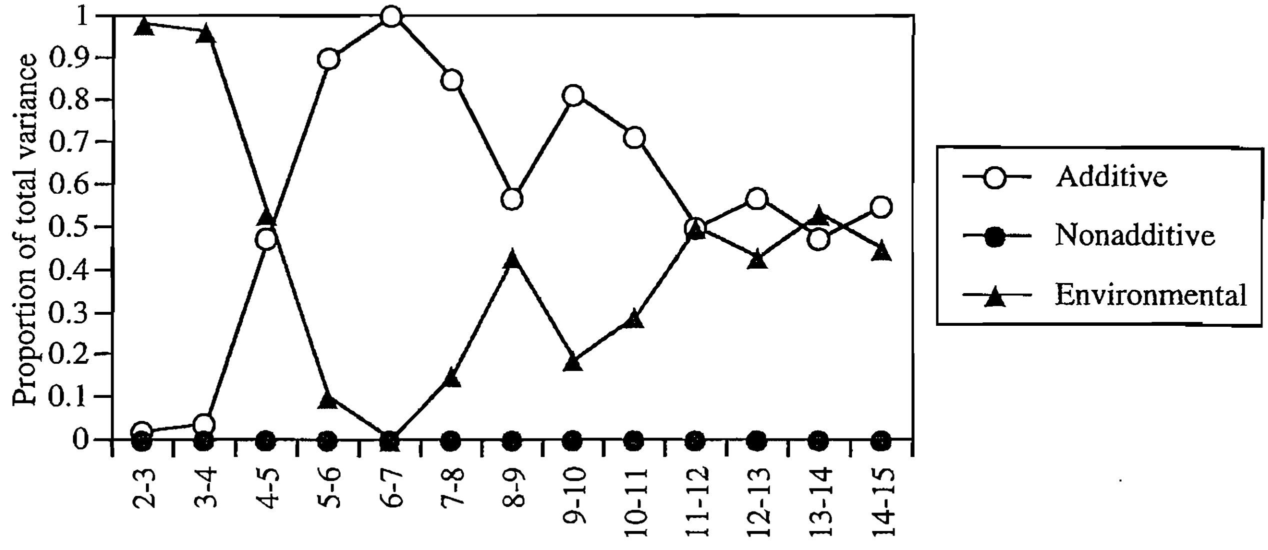

Fig. 4: Age-related changes in the variance components of fibre coarseness in a four parent, radiata pine diallel planted at one site.

Fibre specific surface

Time trends in the variance components of fibre specific surface area (Fig. 5) mirror those found earlier in fibre wall thickness (Fig. 3) because they are inverse related.

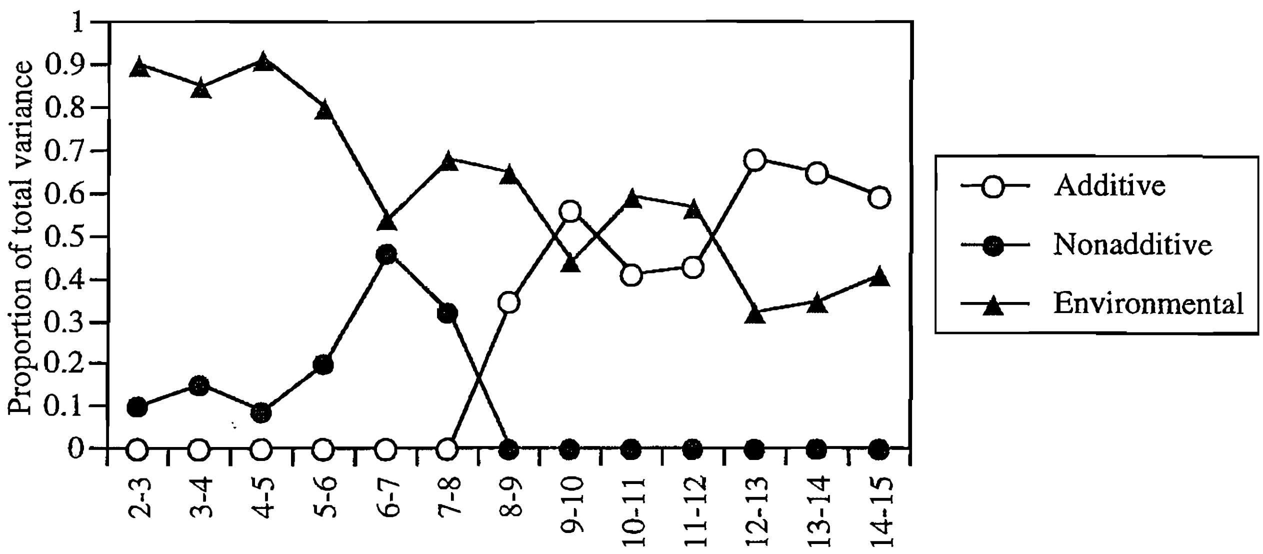

Fig. 5: Age-related patterns of variation in the variance components of fibre specific surface area at breast-height in a four parent, radiata pine, diallel progeny test.

Early selection efficiency

Clearly, selections for fibre perimeter and coarseness were nearly optimal (≥ 80 % of final value) some four to five growing seasons earlier than for other wood quality traits (Fig. 6). Efficiency of selection in fibre coarseness decreased steadily with age after crown closure and was in excess of 100 % because its ADV showed a similar trend (Fig. 4). Matheson *et al.* (1994) found that ADV of basal area under bark stabilises by age 6 years in radiata pine. Therefore, in order to maximise genetic gain they recommended selection for this trait when trees were between 6 and 10 years-old. In this study, selection efficiency was optimal around age 8-9 years by which time nonadditive variance was zero in all traits. Consequently, it is recommended that selection for the pulpwood quality traits coincide with that for basal area under bark.

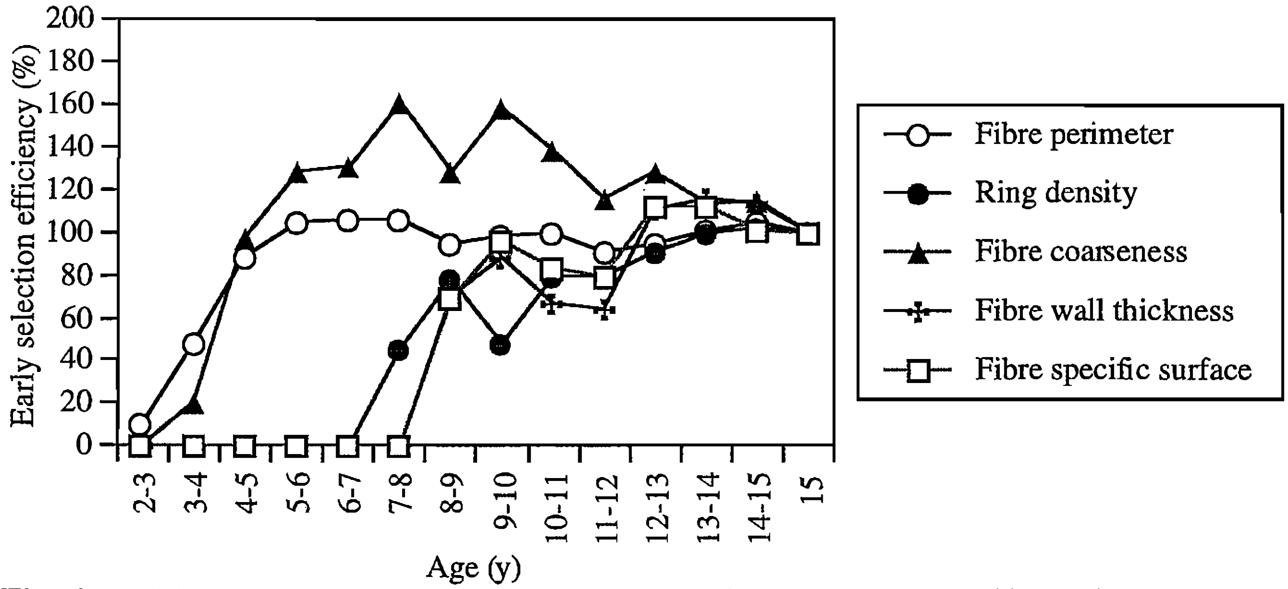

Fig. 6: Radial variation in early selection efficiency of pulp and paper-making traits at a juvenile age i years compared to that at age 15 years in a four parent, radiata pine diallel.

Parental Breeding Values

Take in Fig. 7A-E near here

Progeny of parent 80055 had the largest fibre perimeter at age 2-3 years and highest increment rate thereafter until age 6-7 years (Fig. 7A). Parental breeding values (PBV) increased radially from age 2-3 years to 14-15 years by about 21, 6, 5 and 8 % in parents 80055, 12447, 12038 and 12197, respectively. The age-related changes in fibre perimeter closely mirrored those found earlier by Cown (1975) and Nyakuengama (1991) in fibre diameter and by Evans *et al.* (1995) and Nyakuengama *et al.* (1996 b) in fibre perimeter.

Radial sequences in the PBV of ring density were generally similar for 12038, 12447 and 80055, except between ages 6-7 to 8-9 years and between ages 12-13 and 14-15 years (Fig. 7B. During these periods, PBVs for 12038 and 12197 resembled each other as did those of 80055 and 12447. Wood from 80055 progeny was consistently the least dense while that of 12197 progeny was the densest, especially after crown closure. PBV ranks for density were constant through out the experiment.

PBV of fibre wall thickness (Fig. 7C) showed a radial pattern consistent with that found previously in the same species (Cown, 1975; Nyakuengama, 1991). PBV increased rapidly until age 8-9 years in all parents. Fibres in wood of 12447 progeny were relatively thin-walled in contrast to those of 12197 progeny which had the thickest walls in the experiment, especially after crown closure. Fibre wall thickness in wood of 80055 and 12038 progeny had similar radial trends until crown closure, when fibre wall thickness of the latter parent increased faster. The fibre wall thickness in wood of 80055 and 12447 progeny were essentially similar during the rest of the experimental period.

The PBV ranking for fibre coarseness which was first evident at age 3-4 years remained the same thereafter (Fig. 7D), a pattern resembling that for fibre perimeter and ring density. Fibres in wood of 80055 progeny were the coarsest and those of 12447 progeny were the least coarse in the diallel. Unlike other traits, the difference between fibre coarseness of 80055 and 12197 progeny decreased rapidly with age until crown closure.

Initially, the fibres in wood of 80055 progeny had the highest specific surface area whilst those of 12197 progeny had the lowest (Fig. 7E). However, PBV ranks changed with age so that by crown closure (8-9 years) and thereafter, fibres in wood of 12447 progeny had the highest specific surface area and those of 12197 progeny the lowest. Inspection of Figs. 7B and 7E shows that radial patterns in specific surface area were the inverse of those in fibre wall thickness. This is reflected in the strong, negative genetic correlations (Nyakuengama *et al.,* 1996 c) between the traits which was due to their mathematical relationship (see Method).

Trait means and coefficient of variation

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Overall, fibre coarseness had the highest coefficient of variation and fibre perimeter the lowest in the diallel progeny test (Table 1). Progeny of 80055, consistently produced the least dense wood as indicated by both the mean and median values. On average, the PBV of 80055 for ring density was about 20 % lower than that of the most dense parent, 12197. The range and coefficient of variation of ring density in 80055 progeny were half those of 12197.

In contrast to ring density, parent 80055 had the highest breeding value (PBV) for fibre perimeter (Table 1). However, the range and coefficient of variation in fibre perimeter for 80055 progeny was about three times and twice that for 12197 progeny, respectively.

Parental breeding values for fibre wall thickness were generally comparable between parents (Table 1), except that fibre walls in wood of 12197 progeny were about 5 % thicker than those of 12447 progeny. Results in Table 1 indicate that fibres in wood of 80055 progeny were about 17 % coarser those of 12447, the family with the least coarse fibres (Table 1). Overall, fibre coarseness radially across the stem was about 14 % less for 12447 progeny than for 80055 progeny. The wood of 12447 progeny was also the most homogeneous in fibre coarseness.

Variation patterns in the parental breeding values of fibre specific surface area were similar to those for fibre wall thickness (Table 1).

Correlation of traits and age-related changes

Take in Fig. 8A-K near here

Before crown closure (two to eight years) parental breeding values for fibre coarseness were positively related to those for fibre perimeter (Fig. 8A). At constant fibre coarseness, 80055 progeny had the largest fibre perimeter in the experiment. During this period fibre perimeter increased by 12 % in 80055 progeny and by only 4 % in the other three families. The positive correlation between fibre coarseness and fibre perimeter in 80055 progeny continued after crown closure (between the ages eight to fifteen years-old) (Fig. 8B). This was in marked contrast to the other families, which showed increases in fibre coarseness which were unaccompanied by concomitant increases in fibre perimeter.

Fig. 8C shows that before crown closure, PBVs for fibre coarseness and wall thickness were positively curvilinearly related for 80055 progeny and positively linearly correlated among the other three families. At comparable fibre coarseness, wood of 80055 progeny had the thinnest fibre walls in the experiment. Between ages eight and fifteen years PBVs only for 12038, 12197 and 12447 (and not 80055) showed strong positive correlation between fibre wall thickness and fibre coarseness (Fig. 8D). PBVs for fibre wall thickness were lowest for 12447 fibres which led to their being lowest for fibre coarseness, unlike those for 12197 which were the highest for fibre wall thickness walls and hence also for fibre coarseness. PBVs for fibre properties in 12038 were intermediate. These results confirm the complex dependence of fibre coarseness on fibre size and wall thickness (Seth, 1990; Paavilainen, 1993) and further suggest that both time and genotype are important for these traits.

PBVs for fibre coarseness were unrelated to those for density in 80055 before crown closure (Fig. 8E). On the other hand, there was a weak positive correlation among PBVs for these traits for the other parents which persisted after crown closure (Fig. 8F). During this period PBVs for fibre coarseness were weakly, inversely related to density for 80055.

Before crown closure, PBVs for fibre wall thickness were strongly, positively correlated with those for ring density (Fig. 8G). At a specified ring density, PBVs for fibre wall thickness in 80055 were lowest. Figure 8I shows that the PBVs of ring density were unrelated to those of fibre perimeter. However, PBVs for fibre perimeter in 80055 were consistently the highest in this experiment, accounting for the low PBVs for density in 80055 at all ages. PBVs for density was positively associated with fibre wall thickness, only for 12038, 12197 and 12447 after crown closure (Fig. 8H). During this time PBVs for ring density were also inversely correlated with those of fibre perimeter in 80055 wood (Fig. 8J). Again, PBVs for density in 80055 were the lowest because of its high PBVs for fibre perimeter at comparable wall thickness.

Breeding values of fibre specific surface area and fibre wall thickness indicate that the two traits were perfectly, inversely related before (Fig. 8K) and after (Fig. 8L) crown closure. However, a weak relationship was evident in 80055 trees during the latter period.

Implications for TMP and other wood-based industries

Results from this small 4 x 4 radiata pine diallel clearly echo the concern of Einspahr (1972) that wood quality values obtained for "juvenile wood", which consists largely of earlywood, were unreliable as the heritability of earlywood properties was low. He recommended that progeny testing for wood quality (density) should wait until the trees were 10-12 years-old. Other authors were of the same opinion that juvenile wood density was unstable in the initial 5-25 growth rings in Douglas-fir (Gonzales and Richards, 1988) and 5 growth rings in Cottonwood (*Populus deltoides* Bartr.)(Farmer and Wilcox, 1966). Burdon and Harris (1972) indicated that the phenotypic relationship between density and growth rate parameters were different between the initial 5 growth rings (produced within the green crown) and subsequent growth rings in radiata pine. In a later study on the effect of nutrients and water on radiata pine clones, Harris *et al.* (1978) concluded that "the response to environment changes as trees grow older" as a result "quite different correlations are obtained between environmental factors and wood properties of corewood or outer wood." The same study indicated that tree responses to silvicultural treatments "seemed only to begin to show up in the outer growth rings of these eight-year-old trees." This apparent difference between juvenile and mature wood in their physiological responses to the environment is probably due to the difference in the genetic structures of the two physiological stages.

Given the poor phenotypic relationship between the wood quality (density) of juvenile and mature wood, various authors have recommended sampling only in the outer-half of the increment core in Virginia pine (*Pinus virginiana* Mill.) (Smith and Wahlgren, 1971) and in "a partial radius" in western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and western larch (*Larix occidentalis* Nutt.)(Mitchell, 1964).

Properties of wood directly determine the technological suitability of wood for both mechanical pulping and solid timber end-uses. For example, density is positively correlated with both the modulus of rupture (MOR) and modulus of elasticity (MOE) of clear wood, below fibre saturation point (Walford, 1991). Basic density is considered a good indicator (not predictor) of energy consumption during TMP (Corson, 1991; Kärenlampi, 1992). Energy demand of wood during mechanical pulping appears to be inversely related to its MOE. Consequently, juvenile wood, which contains a larger proportion of flexible, thin-walled and less coarse earlywood fibres, require more energy to refine to a specific standard of freeness than mature wood with less flexible, thick walled and more coarse latewood-like fibres (Kärenlampi, 1992; Rudie *et al.*, 1994; Uprichard *et al.*, 1994; Hatton and Johal, 1995). Valenzuela *et al.* (1990) showed that juvenile wood was up to 1.4 times more plastic than mature wood in radiata pine. In general, the light scattering coefficient of mechanical pulps varies inversely with density (Corson, 1991).

The importance of fibre coarseness in mechanical pulp and paper was studied by many authors. Seth (1990) found that the formation index of a random sheet was directly proportional to the square root of fibre coarseness. At constant solids and fibre length, the web-web tensile strength was proportional to the square root of fibre coarseness. Specific energy was also directly proportional to initial fibre length and fibre coarseness (Miles and Karnis, 1994). Clearly, knowledge of the age-related changes in the variance components of mechanical strengths of wood and fibre traits is of paramount importance to both the pulp and paper-making and solid wood industries.

This study identified three different genetic structures in pulp and paper-making wood traits. Firstly, fibre size was under strong and stable additive genetic influences from as early as 3 to 4 years-old. Secondly, ring density, fibre wall thickness and fibre specific surface area were poorly genetically controlled before crown closure. Thereafter, traits were under stable moderate to strong control. Thirdly, fibre coarseness was strongly controlled until crown closure, like fibre size. However, thereafter its additive variance declined to a level that was comparable to that for fibre wall thickness.

While mechanical pulping and solid wood properties of the trees used in this study were not measured, implications for TMP and other wood based industries are clear. The genetic control of mechanical properties of wood and fibre products would in part reflect the age-related changes in the heredity (and genetic correlations) between traits found in the present study. As the heritability of ring density, fibre wall thickness and fibre specific surface was weak before crown closure, so too would be the genetic control of the mechanical properties they determine. There is ample evidence in the literature to support this contention. For example, Tsehaye *et al.* (1994) found that MOE varied most rapidly in the juvenile wood than in mature wood of 25 year-old radiata pines. Most importantly, they found extremely poor phenotypic correlations between the mechanical wood properties (MOE and MOR) in juvenile and mature wood. Similar radial trends were found earlier in radiata pine by other authors (Hinds and Reid, 1957; Mishoro *et al.,* 1986; Valenzuela *et al.,* 1990; Walford (1991). Other traits have low additive variance in juvenile wood of species other than *Pinus radiata*. For example, Koshy and Lester (1994) found little additive genetic variance in tangential and radial shrinkage of juvenile wood (initial five growth rings) in 18 year-old Douglas-fir. Fujisawa *et al.* (1994) also found that the dynamic modulus of elasticity of juvenile wood (<10 to 15 growth rings from the pith) was unstable in 21 to 26 year-old Sugi. The authors found that clonal differences accounted for about 65 % of variance in dynamic modulus of elasticity. This lack of strong genetic control over density in juvenile wood (less than 10 years) may explain the apparent lack of a consistent density effect on thermomechanical pulping. No comparable study was found on genetic variability of mechanical wood and fibre properties in radiata pine but will be the subject of a future paper.

Conclusions

Age-related changes were found in the variance components and parental breeding values of pulp and paper making traits (ring density, fibre size, wall thickness and coarseness) in a 4 x 4 radiata pine, diallel progeny test. Radial variation patterns of ADV were similar between fibre perimeter and coarseness and between fibre wall thickness and density. In particular, ENV was initially high in all traits but fell more rapidly in fibre perimeter to around 20-30 % of total variance by crown closure (8-9 years). ENV fluctuated around 50-70 % of total variance in fibre wall thickness and specific surface area for the same period. Consequently, genetic control over fibre wall thickness and density was extremely poor before crown closure, in contrast to fibre perimeter and coarseness. ADV of fibre coarseness alone decreased with age after crown closure from an increase in ENV. By age 14-15 years the ADV of both fibre perimeter and ring density was about 80 % of total variance. This variance component accounted for about 60 % of total variance in fibre wall thickness at the same age. The implications of the genetic variance structures on the technological utilisation of wood were discussed.

Interrelationships between pairs of PBV varied between traits and with time. The most unexpected result of the study was that at comparable age the relationships between traits observed in family of parent 80055 were different from those found in families of parents 12038, 12197 and 12447. For example, after crown closure fibre coarseness was positively related to fibre perimeter but not to fibre wall thickness only in the family of 80055 yet the converse was true in the other families. This finding confirms that fibre coarseness is a complex and composite trait, like density, depending on both fibre perimeter and fibre wall thickness.

This experiment was based on a very small set of parents and so numerical estimates of gain would mean very little. However, trends for fibre perimeter and coarseness at younger ages with respect to those at 15 years indicates that selection efficiencies for these traits exceed 90 % when trees are 4 - 5 years old, some 4 to 5 growing seasons earlier than for density, fibre wall thickness and specific surface area. Data in this study suggests that it is necessary to wait until trees are 9 to 10 years old in order to make appreciable gains for these wood properties. Gains per unit time for some traits might be slightly greater if selection were carried out earlier, but would be inadvisable for others (eg. fibre wall thickness).

Acknowledgments

The work was partly funded through an Australian Postgraduate Research Award (Industry) with support from University of Melbourne, Australian Newsprint Mills Ltd. and CSIRO Forestry and Forest Products. Thanks are due to Ms S. Stringer and Ms P. Brennan, Messrs D. Menz, D. Bellingham, N. Caesar, J. Owen, A.G. Brown, Drs S. Nambiar and K.G. Eldridge, G.M. Downes, Dr P.D. Evans (Australian National University), Dr P. Kho and Dr P. Ades (University of Melbourne), Dr R. Cox and Mr P. Volker (Australian Newsprint Mills Ltd.) and other CSIRO staff for their encouragement and constructive criticism.

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fibre radial diameter) and so they were omitted from this study. Moving-averages of pulp and paper-making traits in the initial 15 individual growth rings (corewood) in increment cores were analysed using a diallel least square analysis of variance and covariance in which all effects are treated as random using the DIALL computer program (Schaffer and Usanis, 1969). This program carries out a combining ability analysis (GCA) as in Griffing (1956) and extended to calculate parental breeding values (PBV) from general combining ability effects as follows: PBV = 2*GCA + experimental mean. In order to study age-related changes in the genetic structure of the traits, phenotypic variances were partitioned into environmental, additive and nonadditive genetic components as in Matheson *et al.* (1994). Selection efficiencies in all traits were calculated following the method of Williams and Megraw (1994); $E = [h_j r_{aj.m}/h_m]*100$ %, where: h_j is the heritability for juvenile trait, $r_{aj.m}$ is the juvenile-mature correlation of genetic additive variance and h_m is the heritability for mature trait.

Results and discussion

Fibre perimeter

Additive variance (ADV) in fibre perimeter was initially low but increased rapidly and linearly to a stable level which accounted for 80 % of the total variance by age 5-6 years (Fig. 1). These age-related changes were reciprocated in environmental variance (ENV), except in the opposite direction. Non additive variance (NADV) was initially low (≤ 5 % of total variance) and it remained insignificant through out the life of the experiment. Therefore ADV and ENV were the only important genetic determinants of fibre perimeter.

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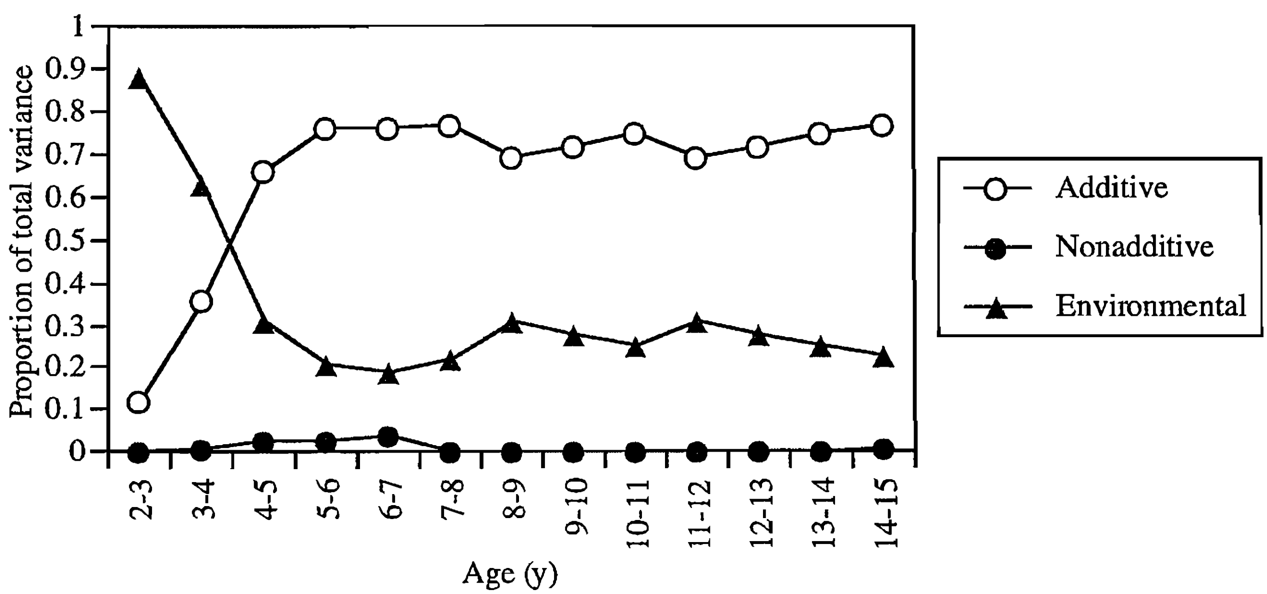


Fig. 1: Radial sequence of variance components in the fibre perimeter in breast-height increment cores of radiata pine.

Ring density

ENV of ring density which was also initially very high (80 % of total variance) and decreased almost linearly with age to a minimum by age 13-14 years (Fig. 2). Conversely, ADV was initially low (20 % of total variance) and declined from age 4-5 to 6-7 years because of an increase in NADV. Thereafter, NADV decreased rapidly and was negligible by age 8-9 years. This fact and a sustained fall in ENV resulted in further significant increases in ADV. When the diallel progeny test was 14-15 years-old ADV accounted for about 75 % of total variance, which is about twice that of ENV (Fig. 2) and similar to the result found in fibre perimeter (Fig. 1).

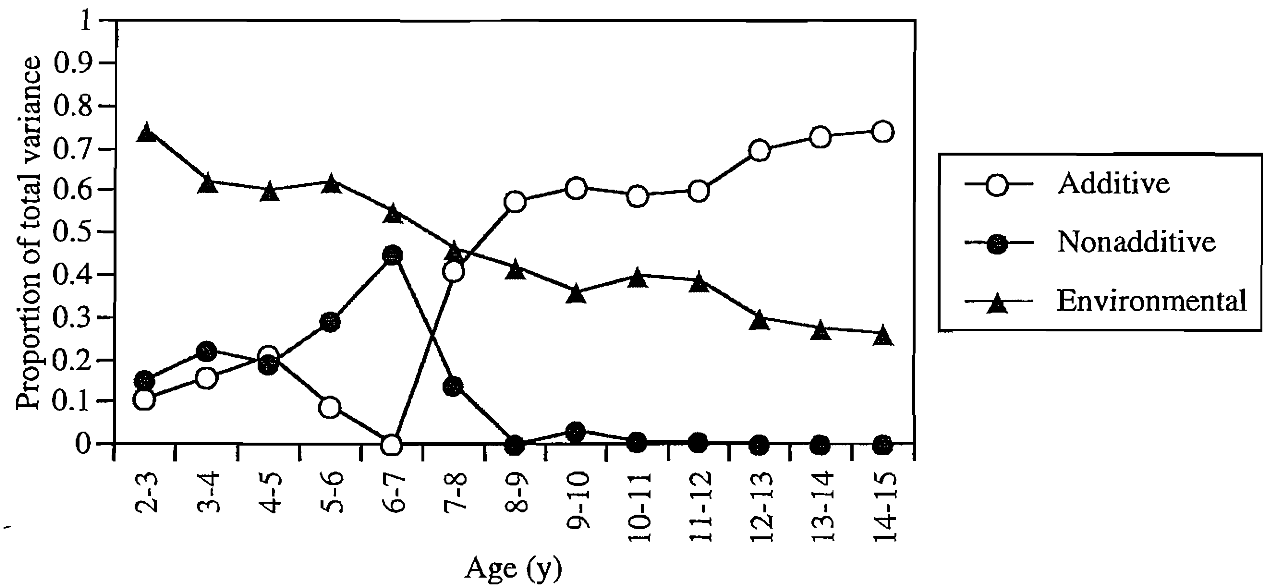


Fig. 2: Age-related changes in the variance components of ring density in the initial fifteen years of a four parent, radiata pine diallel. Data were measured in north-south diametrical cores harvested at breast height.

The radial trend in ADV of density shown in Fig. 2 resembles that found in Douglas-fir from age 6 to 15 years by Vargas-Hernandez and Adams (1992) but differs from that found in clonal Sugi (*Crytomeria japonica* D.Don) by Fujisawa *et al.*, (1993). In this case, broad sense heritability (BSH) fluctuated between 0.2 and 0.3 before the clones were 10 years-old and stabilised around 0.2 thereafter (Fujisawa *et al.*, 1993). Age-related changes in the BSH of basic density found in 25 year-old radiata pine clones by Nicholls (1965) also contradicts the results shown in Fig. 2. Nicholls *cit loc* found that the BSH was high (0.6) near the pith, decreased to about 0.24 around crown closure (8-9 years) and then increased to 0.6 near the bark. Zobel and Jett (1995) noted that this pattern was "diametrically opposite" to their experience. The present study is only similar to that of Nicholls (1965) in that ADV also declined around crown closure. Nonetheless, it is clear that the heritability of density changes with age, but the pattern may vary between seedlings and clones of the same species and between species.

Fibre wall thickness

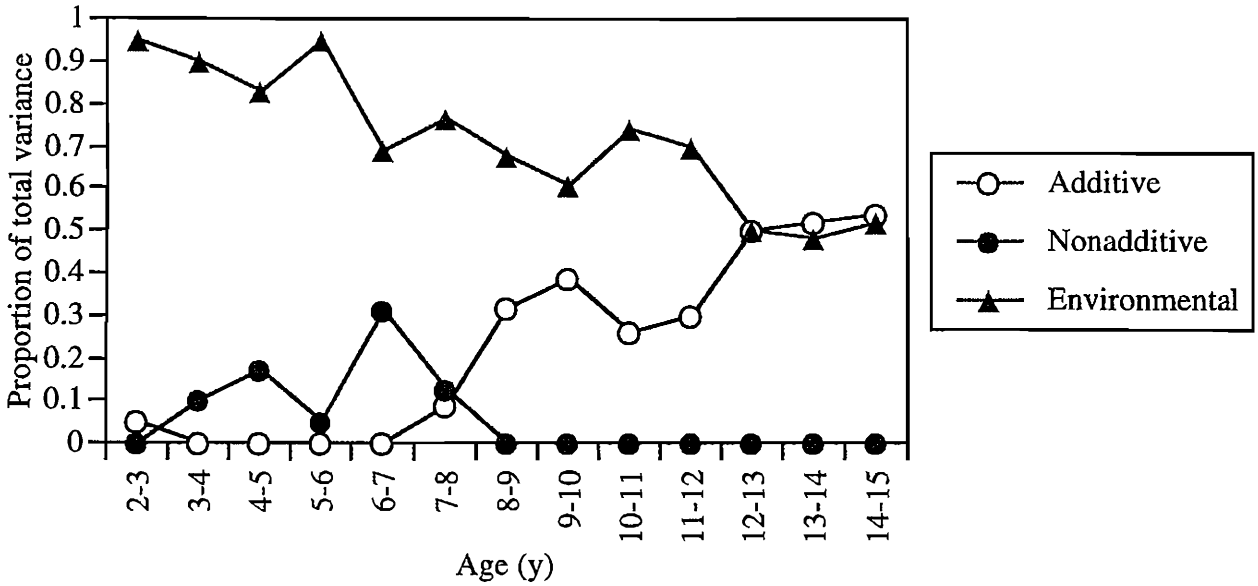
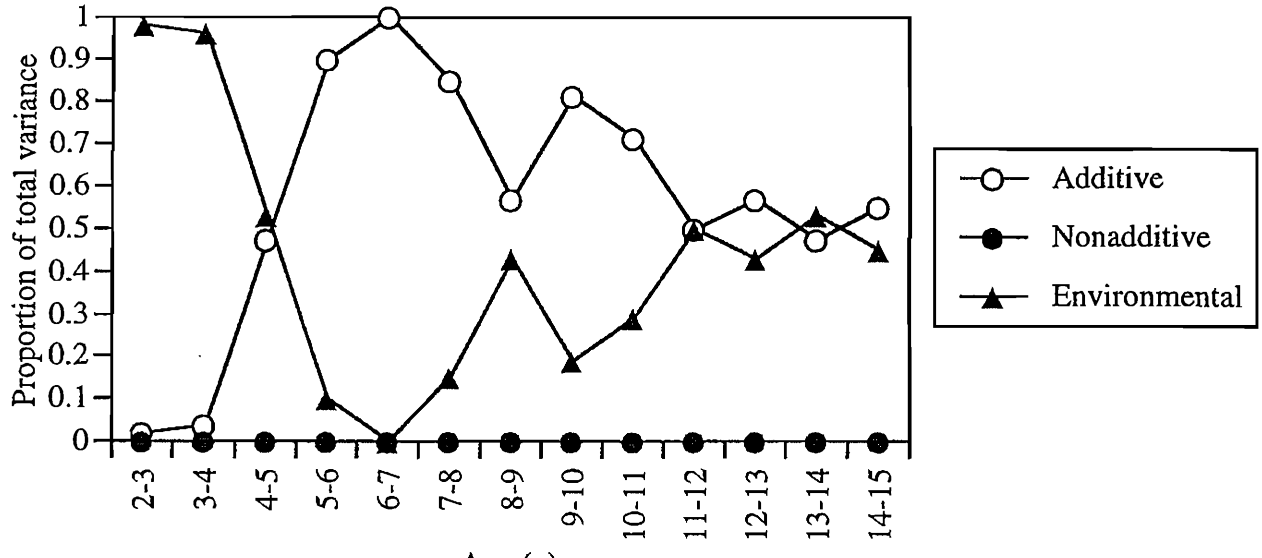


Fig. 3: Age-related variation in variance components of fibre wall thickness measured in the corewood of an unthinned, four parent, radiata pine diallel. Data were collected in north-south diametrical cores taken at breast height in each tree.

Patterns of radial variation in the genetic and environmental variance components of fibre wall thickness (Fig. 3) resemble those of ring density (Fig. 2). Initially, environmental variance accounted for most of the observed phenotypic variance in fibre wall thickness. However, ENV decreased linearly with age to about 60 % of total variance by crown closure, by which time nonadditive variance was zero. Until crown closure the latter had varied inversely and directly to ADV and ENV, respectively. ADV continued to increase with time before ENV increased in response to a drought that occurred when trees were 10 years old. At that time ENV accounted for about 80 % of total phenotypic variance. During the last 3-4 years of the experiment both ENV and ADV each accounted for half of the total variance in fibre wall thickness.

Fibre coarseness

Environmental variance was very high initially accounting for about 95 % of total variance in fibre coarseness (Fig. 4). It decayed rapidly to zero by age 6-7 years, then increased annually to account for about 60 % of total variance by the end of the experiment. ADV varied inversely to ENV since NADV was essentially absent in this trait. The radial pattern observed here was different to that of other traits, possibly reflecting the dual and complex nature of fibre coarseness, namely that it is jointly controlled by fibre perimeter and wall thickness. A reduction in ADV at ages 8-9 and 10-11 years were caused by drought as in fibre perimeter but their effect was more pronounced in fibre coarseness (Fig. 4).



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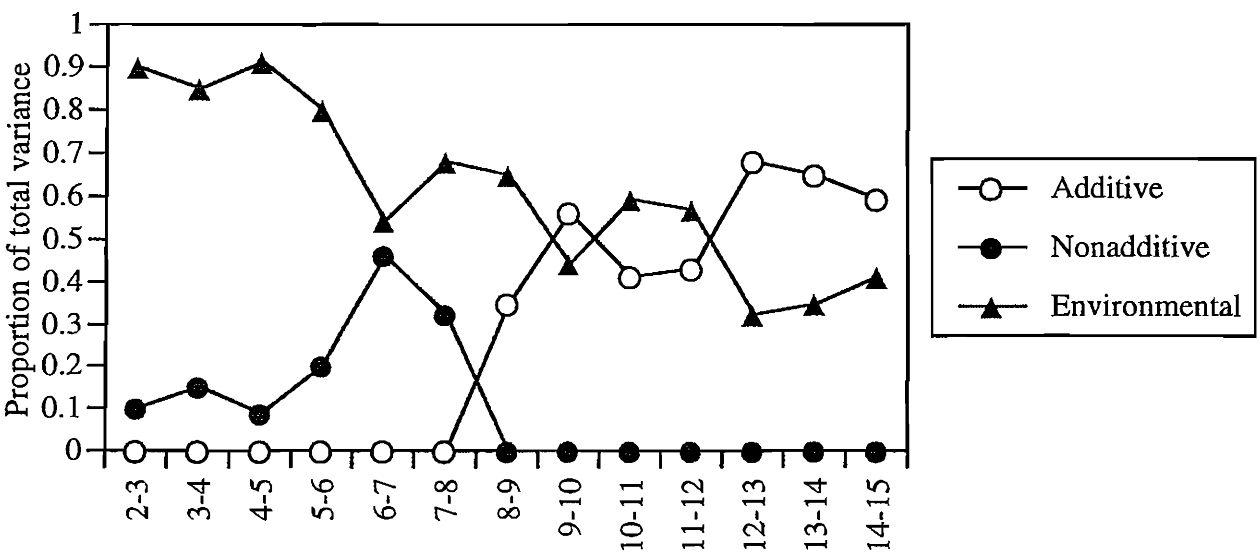

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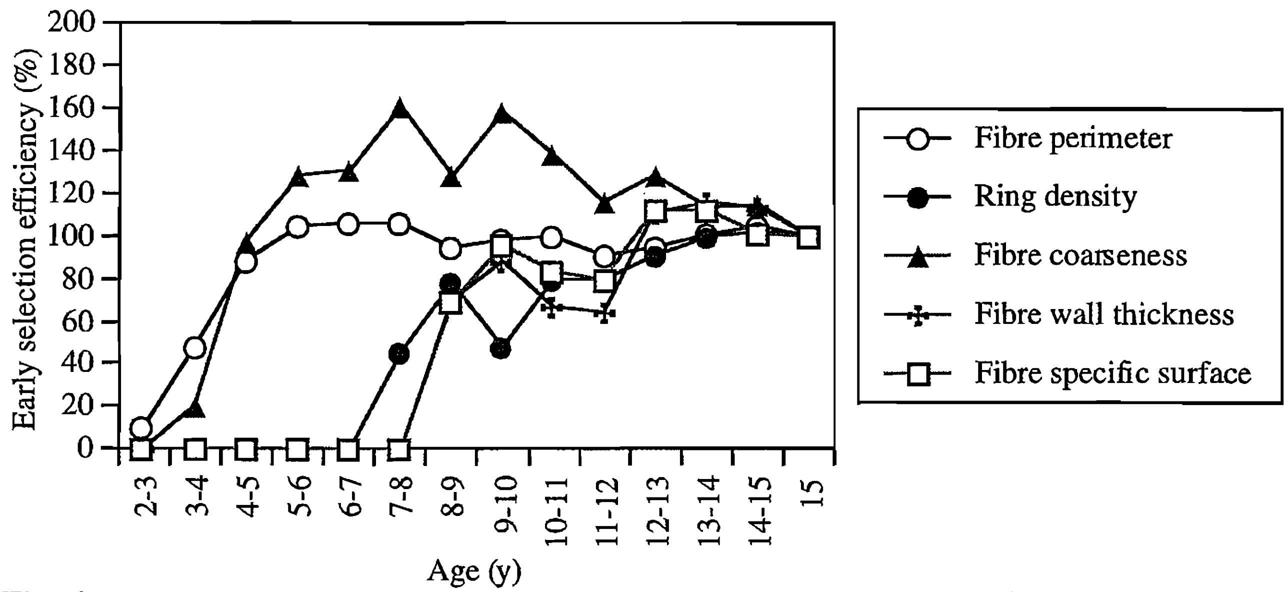

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Variation patterns in the parental breeding values of fibre specific surface area were similar to those for fibre wall thickness (Table 1).

Correlation of traits and age-related changes

Take in Fig. 8A-K near here

Before crown closure (two to eight years) parental breeding values for fibre coarseness were positively related to those for fibre perimeter (Fig. 8A). At constant fibre coarseness, 80055 progeny had the largest fibre perimeter in the experiment. During this period fibre perimeter increased by 12 % in 80055 progeny and by only 4 % in the other three families. The positive correlation between fibre coarseness and fibre perimeter in 80055 progeny continued after crown closure (between the ages eight to fifteen years-old) (Fig. 8B). This was in marked contrast to the other families, which showed increases in fibre coarseness which were unaccompanied by concomitant increases in fibre perimeter.

Fig. 8C shows that before crown closure, PBVs for fibre coarseness and wall thickness were positively curvilinearly related for 80055 progeny and positively linearly correlated among the other three families. At comparable fibre coarseness, wood of 80055 progeny had the thinnest fibre walls in the experiment. Between ages eight and fifteen years PBVs only for 12038, 12197 and 12447 (and not 80055) showed strong positive correlation between fibre wall thickness and fibre coarseness (Fig. 8D). PBVs for fibre wall thickness were lowest for 12447 fibres which led to their being lowest for fibre coarseness, unlike those for 12197 which were the highest for fibre wall thickness walls and hence also for fibre coarseness. PBVs for fibre properties in 12038 were intermediate. These results confirm the complex dependence of fibre coarseness on fibre size and wall thickness (Seth, 1990; Paavilainen, 1993) and further suggest that both time and genotype are important for these traits.

PBVs for fibre coarseness were unrelated to those for density in 80055 before crown closure (Fig. 8E). On the other hand, there was a weak positive correlation among PBVs for these traits for the other parents which persisted after crown closure (Fig. 8F). During this period PBVs for fibre coarseness were weakly, inversely related to density for 80055.

Before crown closure, PBVs for fibre wall thickness were strongly, positively correlated with those for ring density (Fig. 8G). At a specified ring density, PBVs for fibre wall thickness in 80055 were lowest. Figure 8I shows that the PBVs of ring density were unrelated to those of fibre perimeter. However, PBVs for fibre perimeter in 80055 were consistently the highest in this experiment, accounting for the low PBVs for density in 80055 at all ages. PBVs for density was positively associated with fibre wall thickness, only for 12038, 12197 and 12447 after crown closure (Fig. 8H). During this time PBVs for ring density were also inversely correlated with those of fibre perimeter in 80055 wood (Fig. 8J). Again, PBVs for density in 80055 were the lowest because of its high PBVs for fibre perimeter at comparable wall thickness.

Breeding values of fibre specific surface area and fibre wall thickness indicate that the two traits were perfectly, inversely related before (Fig. 8K) and after (Fig. 8L) crown closure. However, a weak relationship was evident in 80055 trees during the latter period.

Implications for TMP and other wood-based industries

Results from this small 4 x 4 radiata pine diallel clearly echo the concern of Einspahr (1972) that wood quality values obtained for "juvenile wood", which consists largely of earlywood, were unreliable as the heritability of earlywood properties was low. He recommended that progeny testing for wood quality (density) should wait until the trees were 10-12 years-old. Other authors were of the same opinion that juvenile wood density was unstable in the initial 5-25 growth rings in Douglas-fir (Gonzales and Richards, 1988) and 5 growth rings in Cottonwood (*Populus deltoides* Bartr.)(Farmer and Wilcox, 1966). Burdon and Harris (1972) indicated that the phenotypic relationship between density and growth rate parameters were different between the initial 5 growth rings (produced within the green crown) and subsequent growth rings in radiata pine. In a later study on the effect of nutrients and water on radiata pine clones, Harris *et al.* (1978) concluded that "the response to environment changes as trees grow older" as a result "quite different correlations are obtained between environmental factors and wood properties of corewood or outer wood." The same study indicated that tree responses to silvicultural treatments "seemed only to begin to show up in the outer growth rings of these eight-year-old trees." This apparent difference between juvenile and mature wood in their physiological responses to the environment is probably due to the difference in the genetic structures of the two physiological stages.

Given the poor phenotypic relationship between the wood quality (density) of juvenile and mature wood, various authors have recommended sampling only in the outer-half of the increment core in Virginia pine (*Pinus virginiana* Mill.) (Smith and Wahlgren, 1971) and in "a partial radius" in western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and western larch (*Larix occidentalis* Nutt.)(Mitchell, 1964).

Properties of wood directly determine the technological suitability of wood for both mechanical pulping and solid timber end-uses. For example, density is positively correlated with both the modulus of rupture (MOR) and modulus of elasticity (MOE) of clear wood, below fibre saturation point (Walford, 1991). Basic density is considered a good indicator (not predictor) of energy consumption during TMP (Corson, 1991; Kärenlampi, 1992). Energy demand of wood during mechanical pulping appears to be inversely related to its MOE. Consequently, juvenile wood, which contains a larger proportion of flexible, thin-walled and less coarse earlywood fibres, require more energy to refine to a specific standard of freeness than mature wood with less flexible, thick walled and more coarse latewood-like fibres (Kärenlampi, 1992; Rudie *et al.*, 1994; Uprichard *et al.*, 1994; Hatton and Johal, 1995). Valenzuela *et al.* (1990) showed that juvenile wood was up to 1.4 times more plastic than mature wood in radiata pine. In general, the light scattering coefficient of mechanical pulps varies inversely with density (Corson, 1991).

The importance of fibre coarseness in mechanical pulp and paper was studied by many authors. Seth (1990) found that the formation index of a random sheet was directly proportional to the square root of fibre coarseness. At constant solids and fibre length, the web-web tensile strength was proportional to the square root of fibre coarseness. Specific energy was also directly proportional to initial fibre length and fibre coarseness (Miles and Karnis, 1994). Clearly, knowledge of the age-related changes in the variance components of mechanical strengths of wood and fibre traits is of paramount importance to both the pulp and paper-making and solid wood industries.

This study identified three different genetic structures in pulp and paper-making wood traits. Firstly, fibre size was under strong and stable additive genetic influences from as early as 3 to 4 years-old. Secondly, ring density, fibre wall thickness and fibre specific surface area were poorly genetically controlled before crown closure. Thereafter, traits were under stable moderate to strong control. Thirdly, fibre coarseness was strongly controlled until crown closure, like fibre size. However, thereafter its additive variance declined to a level that was comparable to that for fibre wall thickness.

While mechanical pulping and solid wood properties of the trees used in this study were not measured, implications for TMP and other wood based industries are clear. The genetic control of mechanical properties of wood and fibre products would in part reflect the age-related changes in the heredity (and genetic correlations) between traits found in the present study. As the heritability of ring density, fibre wall thickness and fibre specific surface was weak before crown closure, so too would be the genetic control of the mechanical properties they determine. There is ample evidence in the literature to support this contention. For example, Tsehaye *et al.* (1994) found that MOE varied most rapidly in the juvenile wood than in mature wood of 25 year-old radiata pines. Most importantly, they found extremely poor phenotypic correlations between the mechanical wood properties (MOE and MOR) in juvenile and mature wood. Similar radial trends were found earlier in radiata pine by other authors (Hinds and Reid, 1957; Mishoro *et al.,* 1986; Valenzuela *et al.,* 1990; Walford (1991). Other traits have low additive variance in juvenile wood of species other than *Pinus radiata*. For example, Koshy and Lester (1994) found little additive genetic variance in tangential and radial shrinkage of juvenile wood (initial five growth rings) in 18 year-old Douglas-fir. Fujisawa *et al.* (1994) also found that the dynamic modulus of elasticity of juvenile wood (<10 to 15 growth rings from the pith) was unstable in 21 to 26 year-old Sugi. The authors found that clonal differences accounted for about 65 % of variance in dynamic modulus of elasticity. This lack of strong genetic control over density in juvenile wood (less than 10 years) may explain the apparent lack of a consistent density effect on thermomechanical pulping. No comparable study was found on genetic variability of mechanical wood and fibre properties in radiata pine but will be the subject of a future paper.

Conclusions

Age-related changes were found in the variance components and parental breeding values of pulp and paper making traits (ring density, fibre size, wall thickness and coarseness) in a 4 x 4 radiata pine, diallel progeny test. Radial variation patterns of ADV were similar between fibre perimeter and coarseness and between fibre wall thickness and density. In particular, ENV was initially high in all traits but fell more rapidly in fibre perimeter to around 20-30 % of total variance by crown closure (8-9 years). ENV fluctuated around 50-70 % of total variance in fibre wall thickness and specific surface area for the same period. Consequently, genetic control over fibre wall thickness and density was extremely poor before crown closure, in contrast to fibre perimeter and coarseness. ADV of fibre coarseness alone decreased with age after crown closure from an increase in ENV. By age 14-15 years the ADV of both fibre perimeter and ring density was about 80 % of total variance. This variance component accounted for about 60 % of total variance in fibre wall thickness at the same age. The implications of the genetic variance structures on the technological utilisation of wood were discussed.

Interrelationships between pairs of PBV varied between traits and with time. The most unexpected result of the study was that at comparable age the relationships between traits observed in family of parent 80055 were different from those found in families of parents 12038, 12197 and 12447. For example, after crown closure fibre coarseness was positively related to fibre perimeter but not to fibre wall thickness only in the family of 80055 yet the converse was true in the other families. This finding confirms that fibre coarseness is a complex and composite trait, like density, depending on both fibre perimeter and fibre wall thickness.

This experiment was based on a very small set of parents and so numerical estimates of gain would mean very little. However, trends for fibre perimeter and coarseness at younger ages with respect to those at 15 years indicates that selection efficiencies for these traits exceed 90 % when trees are 4 - 5 years old, some 4 to 5 growing seasons earlier than for density, fibre wall thickness and specific surface area. Data in this study suggests that it is necessary to wait until trees are 9 to 10 years old in order to make appreciable gains for these wood properties. Gains per unit time for some traits might be slightly greater if selection were carried out earlier, but would be inadvisable for others (eg. fibre wall thickness).

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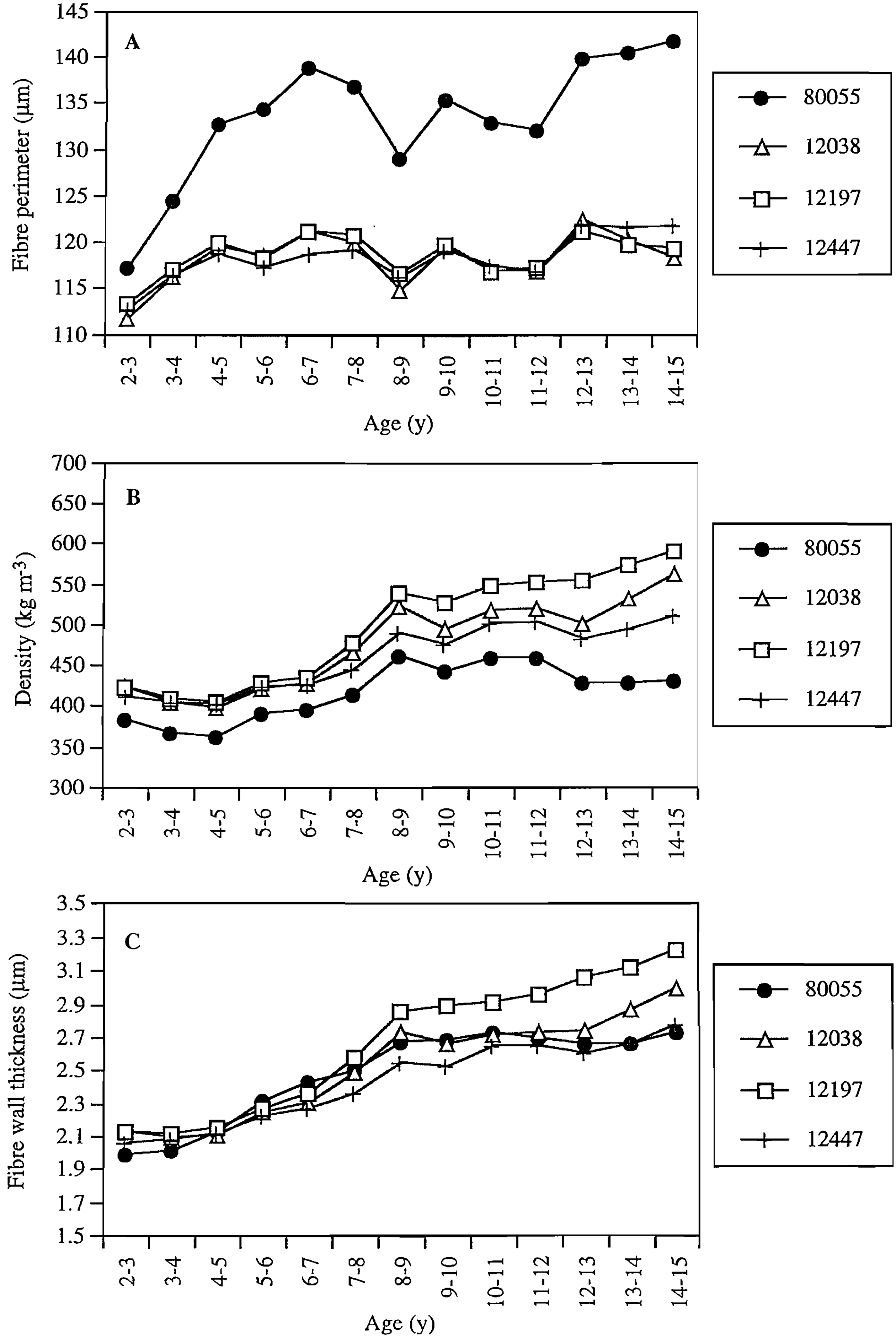
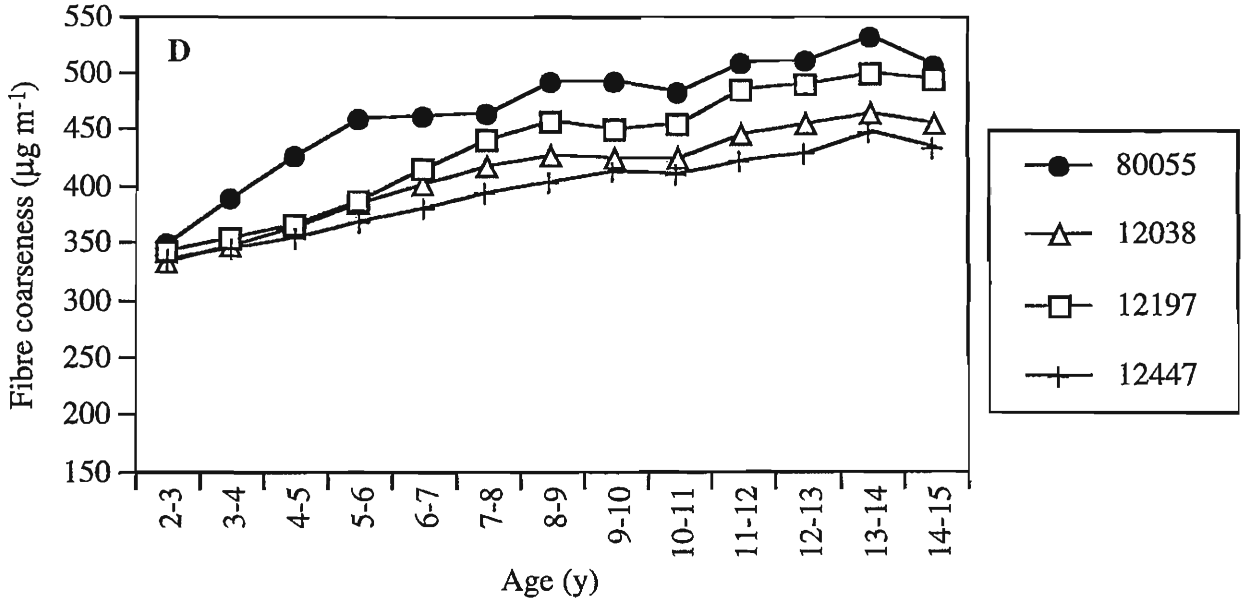
Fig. 7: Radial patterns in parental breeding values of pulp and paper-making traits: fibre perimeter (A), ring density (B), fibre wall thickness (C), fibre coarseness, (D) fibre specific surface area (E) in breast-height cores of radiata pine.




D
Fibre coarseness (µg m-1)
550
500
450
400
350
300
250
200
150
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
Age (y)
80055
12038
12197
12447

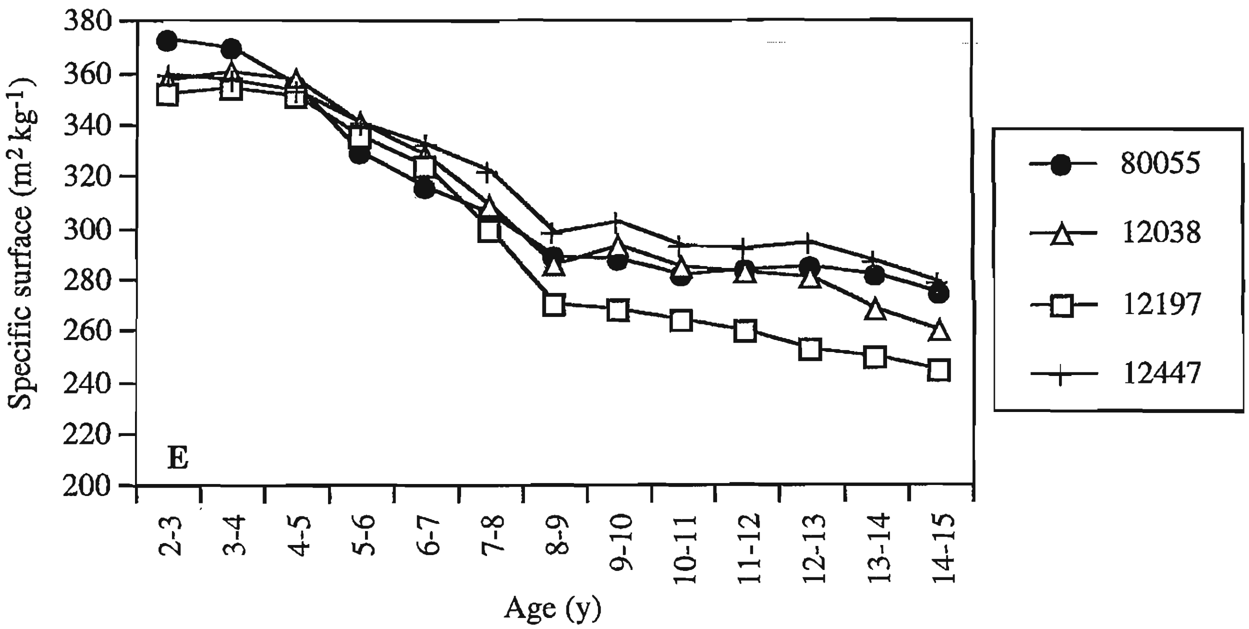
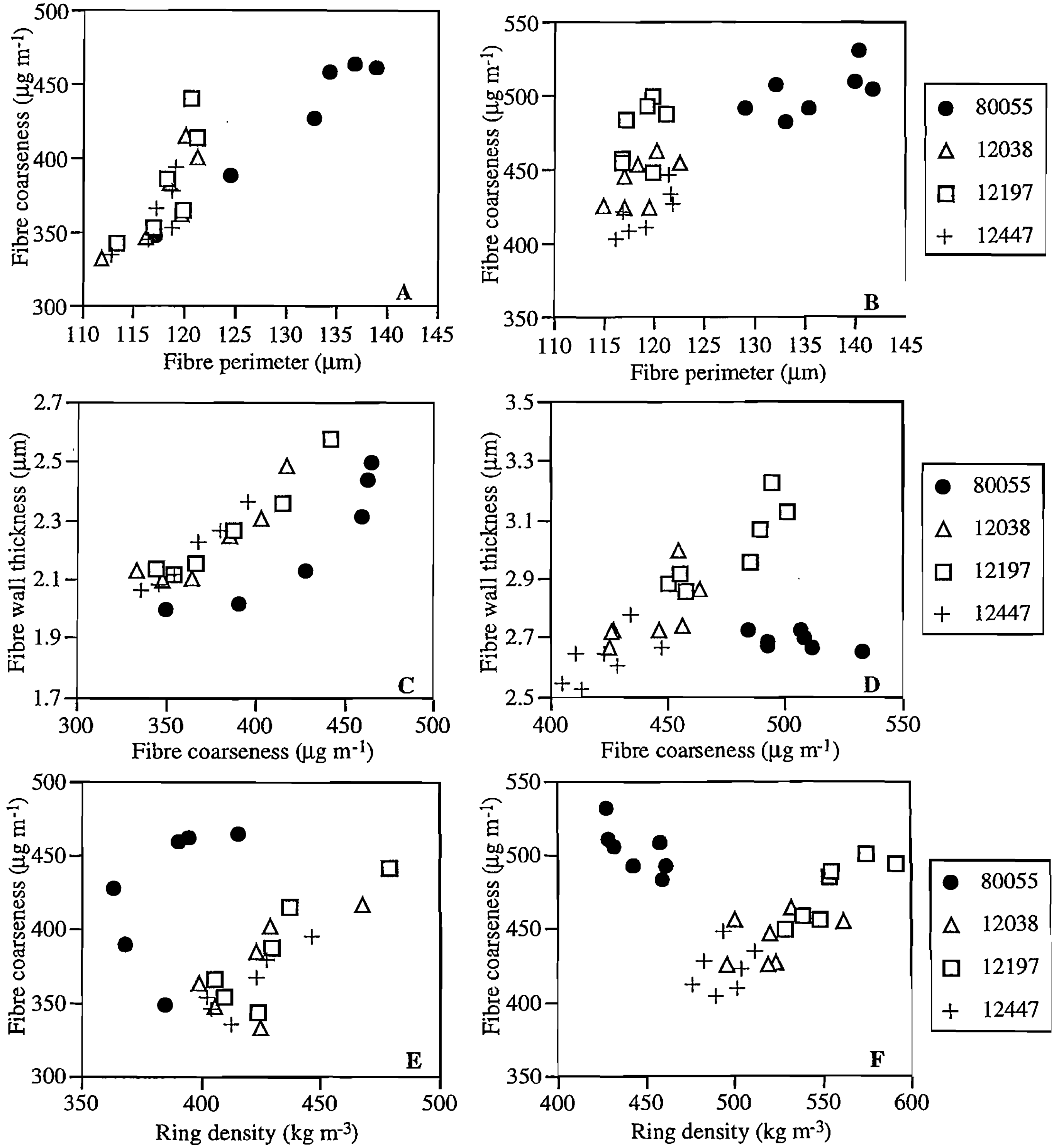
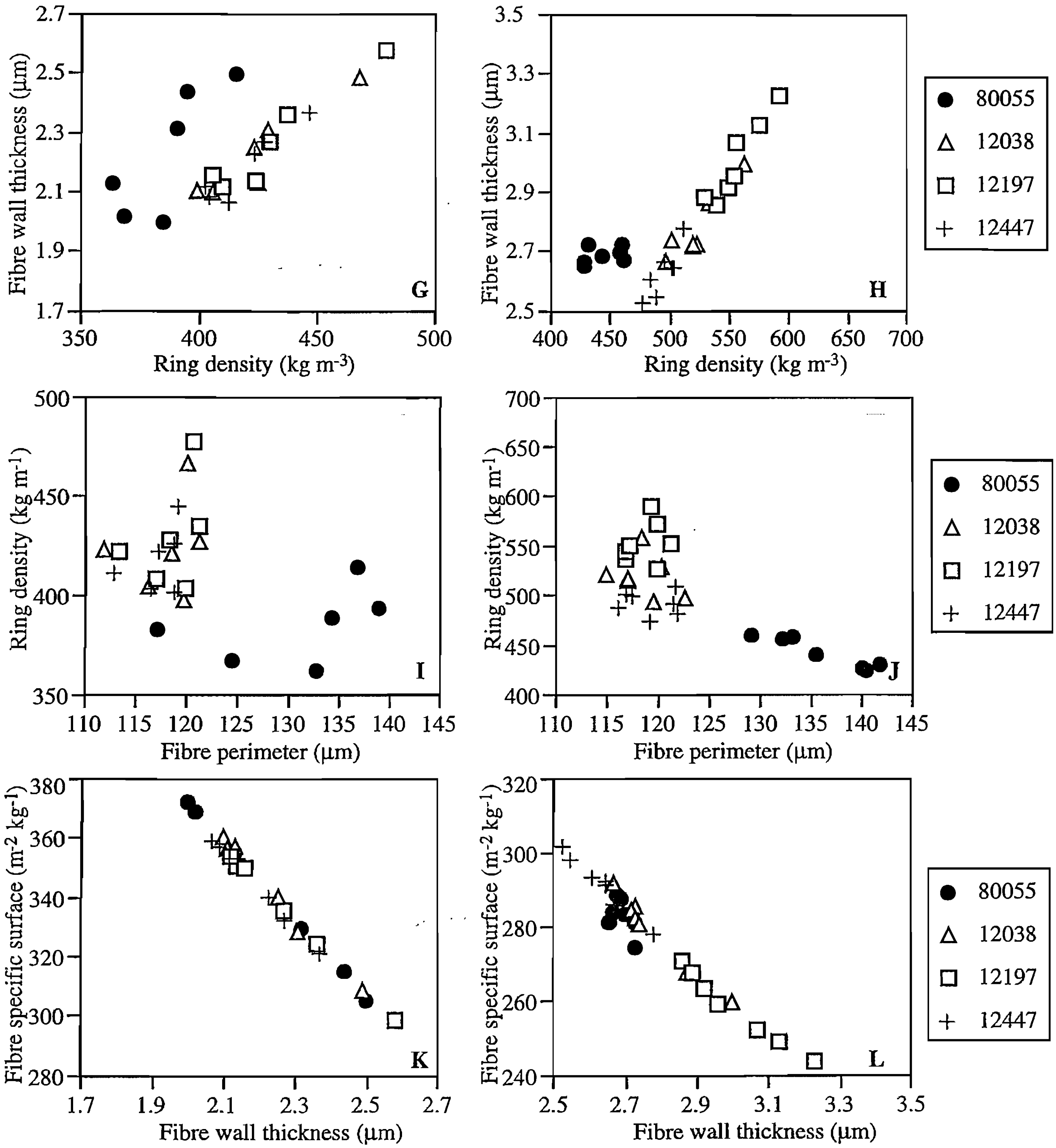

E
Specific surface (m2 kg-1)
380
360
340
320
300
280
260
240
220
200
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
Age (y)
80055
12038
12197
12447

Table 1: Descriptive statistics for parental breeding values of ring density and fibre traits graphically represented in Figs. 7A-E. Pulpwood traits were measured in a four parent, radiata pine diallel planted at a single site.

Parent	Mean	Median	Range	C.V. %
Ring density (kg m^{-3})				
80055	422.82	428.65	121.32	8.91
12038	487.24	498.56	220.42	13.36
12197	508.95	534.03	240.56	15.16
12447	468.08	480.64	165.40	10.51
Fibre perimeter (μm)				
80055	133.66	134.11	24.51	4.96
12038	117.79	118.48	10.75	2.74
12197	118.31	118.92	7.90	2.11
12447	118.28	118.22	9.05	2.12
Fibre wall thickness (μm)				
80055	2.52	2.67	0.94	11.63
12038	2.57	2.70	1.09	13.52
12197	2.72	2.88	1.32	16.35
12447	2.47	2.54	0.92	11.43
Fibre coarseness (μg m^{-1})				
80055	446.62	475.08	369.55	21.37
12038	394.05	421.49	300.60	19.76
12197	415.35	446.18	331.96	21.32
12447	379.28	400.48	285.68	18.79
Fibre specific surface area (m^2 kg^{-1})				
80055	306.75	288.64	116.12	12.09
12038	304.18	289.49	116.94	12.76
12197	289.94	269.98	126.40	15.55
12447	312.29	300.60	101.42	10.32

Fig. 8: Age-related changes in the interrelationship between PBVs before and after crown closure at age 8-9 years for:
fibre perimeter and fibre coarseness before (A) and after crown closure (B);
fibre coarseness and fibre wall thickness before (C) and after crown closure (D);
ring density and fibre coarseness before (E) and after crown closure (F);
ring density and fibre wall thickness before (G) and after crown closure (H);
fibre perimeter and ring density before (I) and after crown closure (J);
fibre wall thickness and fibre specific surface area before (K) and after crown closure (L).
Each point represents a parental breeding value for a moving average of adjacent growth rings over all members of a family.




Fibre wall thickness (μm)
Ring density (kg m-3)
G
H
80055
12038
12197
12447
Ring density (kg m-1)
Fibre perimeter (μm)
I
J
Fibre specific surface (m-2 kg-1)
Fibre wall thickness (μm)
K
L

Properties of plantation-grown eucalypts

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Summary

This report outlines the potential for wood products from short-rotation plantation-grown eucalypts. It also examines different product options which need to be explored, emphasising the successful marketing of wood from silvicultural operations and harvesting residue. Of the fast-growing species grown in Australia, *Eucalyptus grandis, E. saligna* and *E. maculata* present little problem with sawing and drying, have good self-pruning characteristics and good prospects for the recovery of high-quality appearance products. However, some of the eucalypt species naturally occurring in South-Eastern Australia do not perform as well. *E. nitens, E. globulus* and *E. regnans* do not self prune well and the wood is prone to collapse, with specialised processing systems being required in order to minimise drying degrade. However, the light coloured wood from these species is very much in demand for pulp and paper products and also has a market appeal for both sawn and veneer appearance products.

1. Introduction

Australia represents a very small portion of the world forest products scene. Total value of production of solid wood products is less than $A3 billion, with total production of about 3.5 million cubic metres. More than half of the total production comes from the softwood sector, with imports adding a further one million cubic metres. Wood processing industries based on plantation softwoods have expanded largely at the expense of the hardwood industry in the domestic building markets and will continue to do so as the resource doubles in size by the year 2010. At the same time, due to environmental constraints and the need to develop new markets, the hardwood sector is utilising lower quality and younger wood from regrowth forests, simultaneously moving into value-added production, import replacement and developing export markets for higher-value appearance timbers. For example, our furniture industry has a $2.7 billion turnover and is heavily dependent on imported wood for both finished and locally manufactured products. This industry is now placing greater emphasis on the use of Australian materials and looking more toward exporting to Asian markets.

The major species utilised from natural hardwood forests in Australia are the ash-type eucalypts (*E. regnans* and *E. delegatensis*) and stringybarks (*E. obliqua, E. macrorhyncha*) of South-Eastern Australia, the mixed species of the East Coast Forests (*E. pilularis, E. saligna, E. grandis, E. microcorys* and *E. cloeziana*) and the Jarrah-Karri forests (*E. marginata* and *E. diversicolor*) of South-Western Western Australia. Of these major species, only two (*E. saligna* and *E. grandis*), have successfully made the transition to plantation forestry (Figure 1) and are widely planted in many countries. While several of these major species can occur naturally as an even-aged monoculture, site specific requirements, poor growth rates, poor form and susceptibility disease have led to the rejection of most for plantation establishment, while the problem of obtaining satisfactory wood quality within the economic limits of about 30 years for growing a plantation have led to the rejection of others. However, a group of eucalypts which are utilised by the timber industry, but are secondary to the above list of major species, are showing potential when grown under plantation conditions and are currently being evaluated for wood production. Species from the more temperate regions include *E. grandis* and *E. saligna* and from the cooler South-Eastern regions *E. nitens, E. denticulata, E. botryoides* and the different subspecies of *E. globulus*. Research is being carried out at CSIRO Forestry and Forest Products to achieve better growth in these species through genetic selection and silvicultural practices and to evaluate their potential for range of wood products when grown on a rotation length of less than 25 years.

Figure 1
Seventeen-year-old plantation-grown E. grandis, irrigated with winery effluent, Mildura, Australia.

2. Product opportunities

2.1. Sawn products

Traditionally, South-Eastern Australian eucalypts have been quarter-sawn (product surface oriented parallel to log cross-section radius), primarily to control drying degrade, but also to provide better product width stability. Smaller log diameters and high growth stresses combine to limit the potential of quarter-sawing short-rotation plantation-grown eucalypts.

Sawmilling technology developed or imported for the exotic softwood industry has had an influence in the development of a new generation of hardwood sawmilling equipment developed in Australia and suited to the processing of small-diameter eucalypts. Back-sawing strategies have been developed to handle high growth stresses to maximise product recovery and quality (1). The technique also makes it possible to obtain higher-quality products when sawing longer length logs, particularly where the problem of a large knotty core due to poor self-pruning is a major cause of product degrade. However, any advantage in handling longer lengths to facilitate upgrading does not exist to the same extent for pruned logs. In fact it could be preferable to cut the more valuable logs to shorter lengths to improve sawn recovery and reduce losses associated with taper and distortion problems.

2.2 Solid wood product potential of selected eucalypt species

2.2.1 E. regnans and *E. delegatensis*

E. regnans initially attracted most interest in Australia as a plantation species, as it naturally occurs as an even-aged monoculture, but it has proved to be a difficult species to domesticate. The larger dead branch stubs occurring in wider-spaced plantations provide an avenue for fungal attack, resulting in a highly defective log. Pruning has also resulted in fungal attack through branch stubs. Young wood from *E. regnans* and *E. delegatensis* suffers from severe drying degrade unless handled as a thin section, mainly due to excessive collapse and associated collapse checking (1, 2) (Table 1) which occurs during the early stages of drying. Collapse can be recovered by steam reconditioning of wood, but internal checks remain and are exposed during final machining as a severe down-grading problem. Kino veins in sawn wood can also be a major down-grading feature of plantation-grown *E. regnans*.

Table 1

Average number of internal checks in sawn products from young trees for each of four plantation-grown species

Age class	Species			
	E. globulus	*E. nitens*	*E. grandis*	*E. regnans*
15-20	0.9	0.9	0	9.1
21-25	0.5	2.6	0	7.6
30-35	0.4	6.2*	n.a.	3.2

* Results influenced by excessive reaction wood formation in outer growth rings

2.2.2 E. grandis and *E. saligna*

These closely related species originate from the North Coast of NSW. Very promising sawn product results are being achieved with trees at an age of 20-25 years grown in the Murray River basin to control rising water tables. Select quality product out-turn has been of the same order as high-quality product out-turn from 30-year-old clearwood *Pinus radiata*. However there is the added advantage of growing a tree which is self-pruning and quality products are not limited to a pruned height. The wood of *E. saligna* is light brown in colour and usually carries much more figure than most fast-grown eucalypts, with a basic density of around 600 kg/m^3. This wood could demand a premium value for high-value furniture end-use. The wood of *E. grandis* is lighter in colour and slightly less dense. The wood of both species is easily dried. While some collapse does occur during drying, it appears as excessive shrinkage rather than the severe degrade problems which occur in the ash-type eucalypts.

2.2.3 E. globulus

Young plantation-grown *E. globulus* self-prunes reasonably well, not being subject to the same degrade as *E. regnans*, but still requires care when drying for sawn products (3). Even at a young age, it has a density in excess of 600 kg/m^3 (Figure 2), is a high-strength timber (Figure 3) with only minor collapse and little collapse checking (Table 1). The major problems are severe end-splitting of logs (Table 2), distortion during sawing due to high growth stress levels and surface checking during the initial stages of drying.

2.2.4 E. nitens and *E. denticulata*

Again, two very closely related species. While plantation-grown trees do maintain good form, these species are regarded as having very poor self-pruning characteristics. The wood from the two species is indistinguishable and from trees of around 20 years of age is a very pale straw colour, with a density of about 450 kg/m^3. These species rarely produce kino as veins in the wood (which can severely down-grade appearance products), but do produce kino around knots (which appears to act as a barrier to fungal and insect attack) and can produce tension wood even in straight trees if stressed due to high stocking or drought. It will be necessary to prune these species to obtain appearance products. However, while lower branches are plentiful, they are not usually large and are at right angles to the stem, making them easier to prune to a minimum knotty core.

Table 2
Average thickness of end splits and percentage of splits wider than 4 mm thickness

Age (years)	*E regnans*		*E. globulus*		*E nitens*	
	Average thickness (mm)	Percentage wider than 4mm	Average thickness (mm)	Percentage wider than 4mm	Average thickness (mm)	Percentage wider than 4mm
14-19	1.1	0	1.0	0	0.9	0
21-26	2.2	0	1.7	6.6	1.6	8.3
28-34	2.8	14.2	4.2	33.3	1.3	0

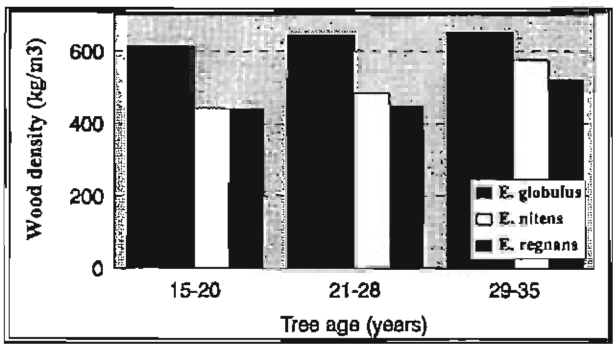

Figure 2
Wood basic density of plantation grown eucalypts, South-Eastern Australia

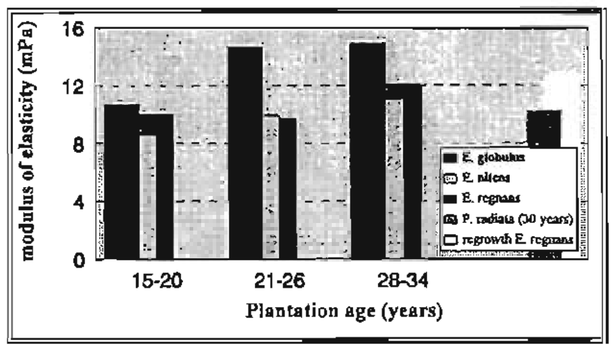

Figure 3
Modulus of elasticity (lower 95 percentile level) for plantation-grown eucalypts (South-Eastern Australia)

Product out-turn trials carried out at CSIRO have shown that knot defects have been the major contributor to poor grade recovery from unpruned stems of these species (Figure 4). Data collected related to every defect on a sawn product. It was possible to reconstruct this data looking at the potential product grade out-turn from pruning. This was done by the re-evaluation of pieces that were outside of a knotty core that would have resulted from pruning. This technique has been validated on studies on clearwood *Pinus radiata* to determine an anticipated grade out-turn resulting from high pruning. These results for *E. nitens* presented in Figure 5 show a high potential for improving product quality by pruning. When applied to *E. regnans*, there was little improvement in product quality due to kino veins and drying degrade, indicating very little potential in pruning that particular species.

2.3 Further processing for high-quality appearance products

A major effort is being made in CSIRO to develop drying strategies, particularly for handling back-sawn products from younger trees, and to advise industry on equipment specifications for the manufacture of high-quality wood products from a wide range of fast-grown eucalypts from both regrowth and plantation-grown resources. Figure 6 outlines the scope of the research requirements. Testing is being carried out to determine shrinkage, stability, strength properties and hardness characteristics of young fast-grown wood. Work is being carried out on machining characteristics and jointing systems, particularly using different forms of phenol and urea formaldehyde based adhesives as acids such as acetic acid in ash-type eucalypts can affect curing and therefore adhesion bond strength. Wood from these projects is being placed with industry to trial the manufacture of furniture items.

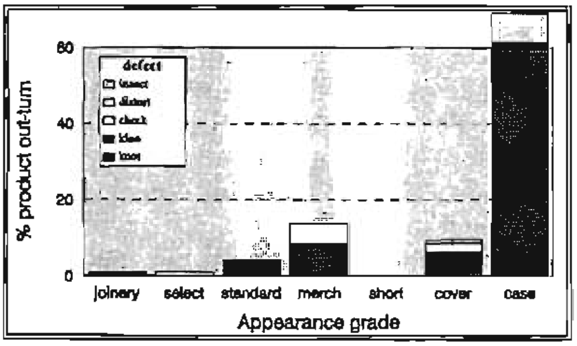

Figure 4
Sawn product out-turn from 30-year-old <u>E. nitens</u>.

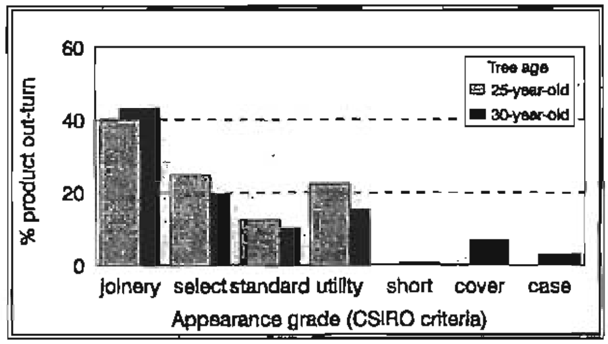

Figure 5
Simulated sawn product out-turn for pruned <u>E. nitens</u> sawlogs, age 30 years.

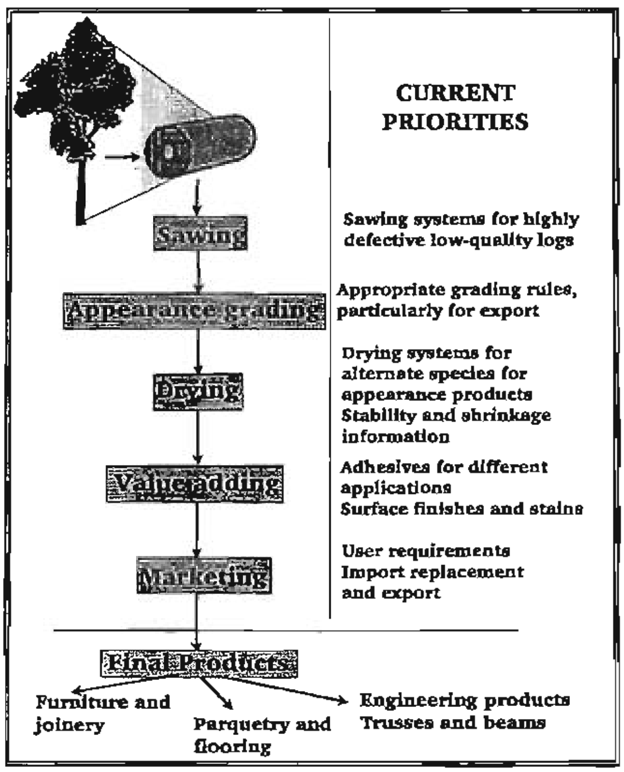

Figure 6
Research priorities for further processing of sawn timber into high-quality appearance products

2.4. Other solid wood products

2.4.1 Veneer products

The greatest emphasis to date has been placed on the manufacture of engineering products from rotary peeled veneer from 30-50 cm diameter logs from both the regrowth and young plantation resource. A detailed study has been carried out investigating the potential of young ash-type regrowth for laminated veneer lumber (LVL) and trials are due to commence on 20-year-old *E. grandis* and *E. saligna* in early 1997 on the potential of these species to provide both appearance and engineering quality products from rotary veneer. Commercial operations on north coast NSW in Australia already provide appearance veneer and form-ply (structural plywood) from 40 year-old plantation-grown *E. grandis*.

Some limited qualitative research has been carried out on veneer products from plantation-grown *E. nitens* and *E. globulus* of 10-20 years of age. The major problem encountered with *E. globulus* has been the end-splitting of logs and veneer billets, causing problems in holding billets on a veneer lathe. Drying did not present a problem, with evidence of only minor collapse. End-splitting problems did not exist with *E. nitens* and no problems were encountered in either peeling or drying veneer, other than some collapse that reduced veneer recovery. *E. nitens* produces a very light coloured veneer, minimising any requirement for bleaching. The lower density would however be expected to result in lower engineering specifications, but pruning should result in a high-quality very light coloured appearance veneer product.

The production of engineering veneer products from young eucalypts is seen by CSIRO as being an area of considerable opportunity, manufacturing larger-section high-strength products to replace the declining global availability of larger sizes from mature native forests. There is only one processing plant in Australia manufacturing Laminated Veneer Lumber (LVL) and is based on softwood, but excellent results have been achieved with a range of eucalypts with trials carried out by both CSIRO and NSW Department of Forests. Most production is based on 65 mm finished thickness, used for beams and lintels for both industrial and domestic use. Higher-density species will normally produce a higher-strength product, but will be more difficult to veneer and require specialised adhesives. Densities from about 450 kg/m^3 to about 650 kg/m^3 would appear to offer the best compromise in peeling, drying and product strength.

The production of 65 mm thickness LVL with random lap jointing of 2.4 mm veneers from regrowth ash-type eucalypt resulted in a product which met Australian F34 specifications, while sawn products from the same resource depending on quality generally met an F14 to F17 specification. LVL of at least F22 engineering grade should be attainable from most young eucalypts. The big advantage for a small log resource is the ability to process wood otherwise down-graded by knot defects into a high-strength engineering product.

2.4.2. Finger-jointed and laminated solid wood products

Wood from *Pinus radiata* is dominating the commodity structural market. While considerable work has been done on mature wood from our major commercial species (*P. radiata, E. marginata, E. pilularis, E. obliqua* and *E. regnans*), we are only just starting to investigate opportunities for young plantation-grown eucalypts. It is anticipated that the emphasis may be on jointing for appearance products rather than structural or engineering products.

Veneer-wrapped products where lower-quality and finger-jointed solid wood is wrapped with a thin appearance quality veneer, preferably from the same species, offers real opportunities for product up-grading from young plantation-grown eucalypts. The ability to produce solid wood and veneer from the same resource overcomes incompatibilities in shrinkage and stability between species. *E. nitens* possibly offers the best opportunity, with appearance veneer produced from pruned butt logs and lower-quality products sawn from unpruned logs upgraded using the veneer. The anticipated higher proportion of higher-quality wood from species with better self-pruning characteristics will not require the same amount of product up-grading, but will still present possibilities, particularly for the improved camouflaging of finger-jointing for upgrading low-quality short lengths. This product is already produced commercially from regrowth ash-type eucalypts in South-Eastern Australia and it is expected that opportunities for upgrading low-quality wood and for market expansion will increase.

2.5 Species for meeting multiple end-use requirements

A major challenge is to improve the potential solid wood product recovery and quality from plantation-grown eucalypts. As shown under current practices (Figure 7), about 60% of the wood volume of a tree of close to 60 cm diameter will be harvested as a sawlog, of which 20% (or 12% of the tree) will end up as select quality solid product and about 60% of the total tree volume will end up as residue. Research work is being carried out to investigate opportunities for residue utilisation and to improve both the proportion of a tree being processed into solid wood products and to improve the quality of products.

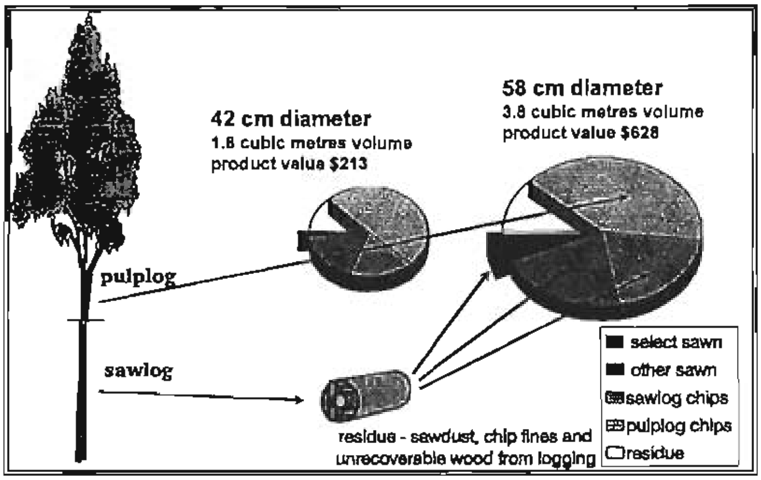

Figure 7

Product out-turn with respect to tree diameter
(based on 50-year-old regrowth E. regnans, Central Highlands, Victoria)

Emphasis needs to be placed on the development of species which can be utilised for a range of end-products. In particular this requirement needs to be considered when growing trees on a rotation length of 20 years or longer, to ensure maximum flexibility to growers in meeting changing market requirements. Therefore, the selection of species which provide wood properties that can combine solid wood values (Figure 8) and are suited to pulp and paper manufacture can be of significant economic benefit to the grower. For example, based on Table 3, which also includes *Pinus radiata* and *Casuarina cunninghamiana*, shows the potential of young fast-grown *E. maculata* for a wide range of products. *E. camaldulensis* has likewise a number of end-uses, but is still under question regarding its suitability for fibre products, leading to problems regarding residue utilisation. *E. globulus* rates highly in this area, but is not regarded as suited for poles due to end-splitting and surface checking.

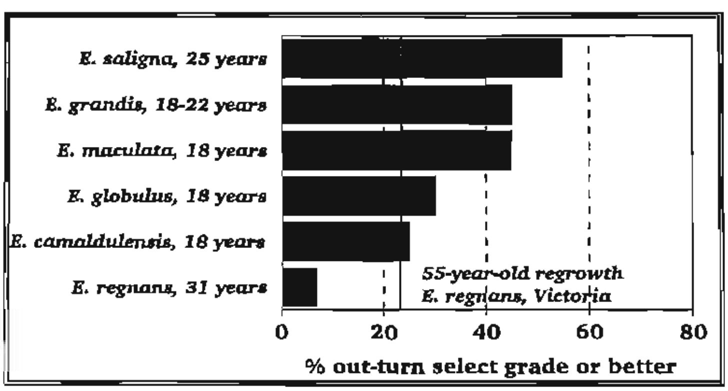

Figure 8

High-quality sawn product potential from different plantation-grown eucalypts from CSIRO research studies

4. Conclusion

The Australian hardwood industry is moving more toward the utilisation of young, fast-grown eucalypts for high-value solid wood products and the option of growing plantations for these products is now much more acceptable than even five years ago. Largely due to developments in processing wood from regrowth eucalypt forests, the processing technology is in place and markets can be identified for wood from plantations. Opportunities are opening up to move plantation-grown eucalypt wood into international markets, but only if user specifications for quality can be met. This resource can assist in meeting an anticipated market demand for high-quality products brought about by the reduction in harvesting of tropical hardwoods for sawn products. The consumer acceptability of a sustainable plantation resource will assist in moving into these markets.

Table 3

Predicted ranking of wood products from selected Australian plantation species grown on a 20-25 year rotation

Species	Round timbers	Sawn appearance	Sawn engineering	Engineering veneer	Fibre composites	Pulp and paper
C. cunninghamiana	*	*	n.s	n.s	?	n.s
E. botryoides	*	*	?	**	**	*
E. camaldulensis	**	*	**	n.s.	n.s.	n.s
E. globulus	*	*	***	*	**	***
E grandis	**	**	**	***	**	**
E. maculata	***	**	***	**	*	**
E. muelleriana	***	?	?	?	?	?
E. nitens	*	**	*	**	**	**
E. regnans	*	*	*	**	**	**
E. saligna	***	***	***	***	*	*
E. viminalis	?	*	**	?	?	***
Pinus radiata	*	*	*	*	***	***

Product suitability

very good	***
good	**
acceptable	*
no reliable data	?
unacceptable	n.s.

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RECENT TRENDS IN PULPING AND BLEACHING TECHNOLOGY

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ABSTRACT

The developments in pulping and bleaching technology are being driven by environmental concerns and market demands for pulp prepared by environmentally acceptable processes.

The main developments in the manufacture of bleached kraft pulp have been in bleaching of the pulp. Chlorine is rapidly being replaced by chlorine dioxide in bleaching sequences. Ozone bleaching is a commercially proven technology and is being used by an increasing number of mills to bleach kraft and sulphite pulps. The use of hydrogen peroxide under pressure at high temperatures for bleaching of kraft pulp has been developed.

Closed cycle systems for bleaching of kraft pulp are being developed but it will be a number of years before a commercial mill will be able to operate continuously in this way.

INTRODUCTION

The main changes which have occurred in pulping and bleaching technology have been related to bleaching of pulp. These changes are being driven by environmental concerns about the effluent from pulp mills as well as by market demands for pulps prepared by environmentally acceptable processes.

The quantities of recycled fibre used by pulp and paper companies has increased appreciably in recent years and this has resulted in a reduced demand for mechanical pulp which it has replaced in some paper products.

A large research emphasis has been on recycling of paper and less effort has been directed towards mechanical pulping in recent years. Some aspects of paper recycling such as deinking have been studied intensively. Mixtures of enzymes have been used for this purpose and pilot plant trials have been carried out.

The developments in kraft pulping and bleaching technology are discussed below.

Kraft pulping

The kraft pulping process can be modified to increase the amount of lignin removed during pulping. This modification can be used for both continuous and batch processes. Extended delignification is becoming more common in bleached kraft pulp mills, especially those using totally chlorine free (TCF) bleaching sequences. A low lignin content is necessary for pulp entering bleach plants with TCF sequences because the bleaching chemicals are not as efficient at removing the residual lignin from the pulp as chlorine-containing chemicals.

Oxygen delignification

Oxygen delignification is used after the pulping stage to reduce the lignin content of the pulp entering the bleach plant. Since 1990 the quantity of oxygen-delignified pulp manufactured per annum on a world-wide basis has doubled and there are about 185 plants at the present time. The incorporation of an oxygen delignification stage into a bleached kraft pulp mill has been facilitated by the development of pulp mixers which can efficiently mix oxygen gas with pulp at medium pulp consistency (about 10%). Most of the procedures in a bleached kraft pulp mill are done at this consistency.

Chlorine dioxide substitution

One of the biggest changes in bleaching of chemical pulp has been the replacement or partial replacement of molecular chlorine with chlorine dioxide in bleaching sequences. Elemental chlorine free (ECF) bleaching involves the replacement of all the molecular chlorine and the term ECF is usually interpreted to mean bleaching with chlorine dioxide as the only chlorine-containing bleaching chemical. The substitution of chlorine dioxide for molecular chlorine has taken place very rapidly in some countries. For example, in Sweden molecular chlorine is no longer used for bleaching pulp. The main benefit from the use of chlorine dioxide is in the amount and nature of the organochlorines formed during bleaching. Complete substitution of chlorine dioxide for chlorine in a bleaching stage reduces the amount of organochlorines in the filtrate by a factor of about 5. The nature of the organochlorines is also different. The amounts of polychlorinated phenols in the filtrate are reduced to very low levels and this lowers the toxicity. The level of dioxin in effluent is lowered to close to or below the analytical detection limits when 100% chlorine dioxide is used for bleaching (1).

A large proportion of the material in the filtrate from bleaching of kraft pulps is high molecular weight (molecular weight greater than 1000). When 100% chlorine dioxide is used there is less high molecular weight material than when 100% chlorine is used (1). The chlorine content of this material is 5-10 times lower than that from chlorine bleaching (1). This means that when the high molecular weight material is degraded in the environment the level of chlorination in the low molecular weight products will be very low. Analyses of the high molecular weight material in untreated bleach plant effluents from mills using 100% chlorine dioxide showed that the chlorine content was comparable to that of naturally occurring humic material (2).

Ozone bleaching

The development of ozone bleaching technology has been very rapid over the last ten years. Commercial scale operations commenced in 1992, and by 1997 there will be 18 ozone bleaching plants throughout the world. The main driving force has been the need to supply a European market which is demanding TCF pulp with a high brightness. The ease of recycling the effluent from an ozone bleaching stage to the chemical recovery system of a kraft pulp mill has been an additional factor.

Two technical developments in the generation of ozone occurred which enabled it to be used for bleaching of pulp (3). Ozone is usually manufactured by passing oxygen through a corona discharge. In the first development the concentration of ozone in oxygen was able to be increased from 6-8% in the late 1980's to 14% in the mid 1990's. Secondly, the electrical energy required for its generation was decreased significantly and this reduced the cost.

Ozone is a powerful oxidising agent and can replace chlorine and chlorine dioxide in the first stage of a conventional bleaching sequence. Ozone is used to bleach sulphite and kraft pulps as well as recycled fibre. Ozone treatment of pulp is usually followed by a peroxide stage.

Hydrogen peroxide

Hydrogen peroxide is not an efficient delignifying agent and is used mainly to bleach high yield pulps. Recently, it has become an important chemical for bleaching of kraft pulps in TCF bleaching sequences. A key requirement for the successful use of peroxide is that the content of heavy metal in the pulp must be low while the magnesium level should be as high as possible. The magnesium protects the carbohydrates from oxidative damage during the peroxide treatment. The Eka Nobel company in Sweden developed the Lignox® process which is a two-stage procedure in which the first step applies these principles and the second is an alkaline peroxide treatment (4, 5, 6, 7). Additional hydrogen peroxide stages or treatment with ozone or peroxyacids result in pulps with high brightness levels.

An important advance in hydrogen peroxide bleaching technology has been the development of pressurized hydrogen peroxide (PO) in which the pulp and bleaching liquor are heated at a temperature of 100-120°C in a vessel pressurized with oxygen. This technology was developed by Kvaerner Pulping Technologies and has been adopted by a number of mills over a short period (8, 9). The key features of this technology are the use of a high pulp consistency, a pulp with a low lignin content, a high temperature and an oxygen pressure of at least 0.5 MPa. The high temperature results in rapid bleaching and a high consumption of the applied peroxide charge. For example, a brightness of 83% ISO was obtained with a softwood kraft pulp in about 2 hours when pressurized peroxide bleaching was used compared with 15 hours with conventional bleaching at atmospheric pressure (8).

A big advantage of the (PO) process is that a single stage can replace several atmospheric pressure stages in a bleach line. It has been shown that the oxygen used to pressurise the reaction vessel contributes to the beneficial effects of the process.

The residual lignin in kraft pulp, especially after an oxidative treatment, is relatively unreactive towards hydrogen peroxide at temperatures in the range 60-80°C. Addition of nitrilamine (cyanamide) to alkaline hydrogen peroxide activates the hydrogen peroxide and makes it more reactive (10, 11). Laboratory studies have shown that this modification is effective with kraft pulps but so far it has only been used on an industrial scale for the peroxide bleaching of sulphite pulp.

Peroxyacids

Peroxyacids are formed when acids such as acetic acid and sulphuric acid are reacted with hydrogen peroxide. Peroxyacids delignify pulp and have a bleaching action. The reaction does not proceed to completion and the equilibrium mixture contains the peroxyacid and water as well as the acid and hydrogen peroxide. An important advance has been the commercial availability of distilled peroxyacetic acid which is a selective delignifying agent for kraft pulp and a possible alternative to ozone in a bleaching sequence. Peroxyacetic acid bleaching trials have been carried out at three pulp mills in Sweden and were successful (12).

Enzymes

Finnish researchers found that treatment of kraft pulps with hemicellulases improved their bleachability. Hydrolysis of a small proportion of the hemicelluloses in pulp by enzymes gives a higher final brightness or a saving in bleaching chemicals to reach a particular brightness. The main hemicellulase required to improve the bleaching of kraft pulp has been found to be xylanase.

The use of xylanase can be beneficial with bleaching sequences based on chlorine-containing chemicals as well as with TCF sequences. The savings in bleaching chemicals have to be balanced against the loss in pulp yield and the cost of the enzyme.

Many mills throughout the world have had mill trials with xylanase and some are using it on a continuous basis. For example, in Canada in 1994, 750,000 tonnes of pulp were treated with xylanase prior to bleaching (13).

Closed cycle bleach plants

Concern about the low level of residual toxicity in effluent from modern bleached kraft pulp mills has resulted in considerable research effort being directed towards the development of bleach plants with closed water loops. There are about twelve kraft pulp mills throughout the world actively involved in the development of closed cycle technology.

Most of the research involves the use of TCF bleaching sequences because there are no problems with sodium chloride in the chemical recovery system of the mill. However, there are two current developments which employ ECF sequences. Commercially proven bleaching technologies and the high quality of the bleached pulp were the reason for interest in these sequences. Also, there are a large number of ECF bleach plants throughout the world which could be modified to incorporate the technology.

The mills using TCF sequences recycle the filtrates from the alkaline bleaching stages to the chemical recovery system. The filtrates from the acidic stages are only partly recycled as they contain most of the heavy metals removed from the pulp and present the greatest challenge for final closure of the bleach plants.

The two developments involving ECF bleaching have different approaches. The joint venture between the Jaakko Pöyry and Eka Nobel companies has developed a procedure in which part of the alkaline filtrate from the bleach plant is added to the chemical recovery system of the pulp mill and the remainder is processed in a separate system (14). The major portion is evaporated and oxidised at high temperatures with oxygen in a specially designed reactor. The alkaline brine from the reactor contains the heavy metals precipitated as carbonates and imbedded in insoluble calcium carbonate. It is claimed that in this form they present no problems with disposal in landfill. The condensate from the evaporation stage can be used as process water in the bleach plant. The second development by the Champion International Corporation uses an ion exchange procedure to remove non-process elements such as calcium and transition metals from the acidic filtrate (15). The filtrate is combined with the alkaline filtrate and recycled to the chemical recovery system. Potassium and chloride are removed from the system by taking advantage of the preferential accumulation of these elements in the precipitator dust from the recovery boiler. The process is being studied on a commercial scale in North Carolina, USA.

The Husum mill of the MoDo Paper company in Sweden manufactures bleached hardwood kraft pulp with a bleaching sequence using oxygen, ozone, peroxide and chlorine dioxide. It has been possible to run the bleaching process completely counter-currently with no filtrate discharged as effluent for about 25% of the time (16). The chloride in the system is removed by scrubbing the hydrogen chloride from the recovery boiler flue gases and removal of the precipitator dust which is rich in sodium chloride.

A number of issues such as scaling of equipment and accumulation of heavy metals have to be solved before a bleached kraft pulp mill can run continuously with a closed cycle bleach plant.

Closure of bleach plants attached to sulphite mills has been more successful than those bleaching kraft pulp. A bleached sulphite mill in Sweden has been operating as a closed cycle process since 1991. The mill uses a sodium-based acid sulphite pulping process and a Stora Chemical recovery system.

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THE EFFECT OF A TROPICAL WHITE POCKET ROT, *Rigidoporus lineatus,* ON THE WOOD AND KRAFT PULPING PROPERTIES OF *Pinus elliottii* STORED LOGS AND WOODCHIP PILES

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ABSTRACT

The Queensland Department of Primary Industries stored almost 400,000 m^3 of slash pine (*Pinus elliottii*) logs under water sprays at Beerburrum, Queensland, following a plantation fire. After a little over a year, a tropical white pocket fungus (*Rigidoporus lineatus*) was noticed on some of the logs. A collaborative research program with CSIRO was initiated to determine the effects of the fungus on the kraft pulping and papermaking properties of the wood. Whole logs from the storage facility, residues from a sawing trial, and green wood from freshly felled trees, were sampled. In addition, three corresponding woodchip piles were created from similar material, and sampled after approximately 6- and 12-weeks storage in the open.

Basic density varied considerably according to the source of the wood. Nevertheless, it was clear that the sawmill residues had a higher density and a higher kraft pulp yield than wood from whole logs. On storage in the chip piles, there was some evidence of a small reduction in basic density over the first six weeks, but pulp yields were not adversely affected by extended storage. The correlation between pulp tearing resistance and wood basic density in the fresh samples suggested that the presence of the fungus had no effect on pulp strength. After the first six weeks of storage in the chip piles, pulp tearing resistance was lower, but the relationship with basic density was still consistent between the samples, suggesting that the decreased pulp strength was unrelated to the presence of the white rot.

INTRODUCTION

The Queensland Department of Primary Industries stored almost 400,000 m^3 of slash pine (*Pinus elliottii*) logs under water sprays at Beerburrum, Queensland, following a plantation fire. After a little over a year, a tropical white pocket fungus (*Rigidoporus lineatus*) was noticed on some of the logs. A collaborative research program with CSIRO was initiated to determine the effects of the fungus on the kraft pulping and papermaking properties of the wood. A program of sampling and testing was agreed to determine whether kraft pulp yield or strength had been adversely affected. The program was later extended to investigate the effect of outside storage on chip pulping quality, as there was concern that the white pocket rot might continue to grow inside chip piles.

EXPERIMENTAL

Wood samples

Broadly, the wood samples tested can be divided into three groups: residues from trial sawing of the stored logs, chips from whole logs taken from the Beerburrum log storage facility, and chips from freshly felled green logs; the latter included as a control. Each group was comprised of one freshly obtained chip sample, and one or more samples of chips from piles stored for different times in the open. Representative composites for pulping were assembled by mixing chips from six logs or from six sub-samples taken from the interior of each chip pile. The origin of each sample is summarized in Table 1.

Table 1 - Origin of wood chip samples

Origin	Type	Age in weeks
Sawmill residues	Fresh chips	0
	Chip pile A	6 12
Green logs	Fresh chips	0
	Chip pile B	12
Stored logs	Fresh chips	0
	Chip pile C	7 13

Screening

Each chip sample was passed over screens with 32 mm and 6 mm diameter circular openings to remove oversize and pin chips that can adversely affect pulping results. The accepts were placed in sealed, heavy-duty polyethylene bags and stored at <5°C until required for the pulping tests.

Moisture content

The moisture content of each wood sample was determined in triplicate by drying 100 gram lots in an oven at 105°C for 3 days.

Basic density

The basic density of each composite woodchip sample was measured according to the draft Australian/New Zealand Standard AS/NZS 1301.001s, using the alternative boiling method.

Kraft pulping

Kraft pulps were prepared in stainless steel pressure vessels of 3-litre capacity, held horizontally and rotated in an electrically-heated air bath. The active alkali charge was varied with the aim of producing pulps of Kappa number 30. The following pulping conditions were kept constant for all pulps: 500 g (oven dried equivalent) of wood chips, 4:1 liquor to wood ratio, sulfidity 25%, 70 minutes to temperature, 113 minutes at 165°C, H factor of 1300.

After the cooking stage, each sample was initially rinsed with approximately 20 litres of cold water, then disintegrated at about 5% concentration for 5 minutes. The pulp was washed free of black liquor using more cold water. Shives were removed from the pulps using a Packer screen with 0.2 mm wide slots. The screened pulp was dewatered in a press to about 30% consistency and crumbed mechanically for 20 minutes. Pulp moisture content was determined in triplicate by drying 10 gram lots in an oven at 105°C overnight. The yield, as percentage of oven dry pulp to oven dry wood, was calculated. The Kappa number of the screened pulp (a measure of residual lignin content) was determined according to Australian/New Zealand Standard AS/NZS 1301.P201m-86.

Papermaking properties

Handsheets were prepared according to AS/NZS 1301.203s:1993 from unbleached pulp beaten in a PFI mill using 24 g (o.d.) pulp charge, 10% stock concentration and 3.33 $N.mm^{-1}$ beating load (AS/NZS 1301.209rp-89), and tested according to AS/NZS 1301.208s-89.

RESULTS AND DISCUSSION

Basic density

Loss in wood substance caused by fungal attack can be monitored by measuring the reduction in basic density, as green volume changes are small even up to losses of 40% of mass on a water extracted basis (Feist *et al.* 1971). The basic densities of the samples are given in Table 2.

Table 2 - Basic densities

Origin	Type	Age in weeks	Basic density $kg.m^{-3}$
Sawmill residues	Fresh chips	0	564
	Chip pile A	6	551
		12	549
Green logs	Fresh chips	0	522
	Chip pile B	12	452
Stored logs	Fresh chips	0	467
	Chip pile C	7	479
		13	477

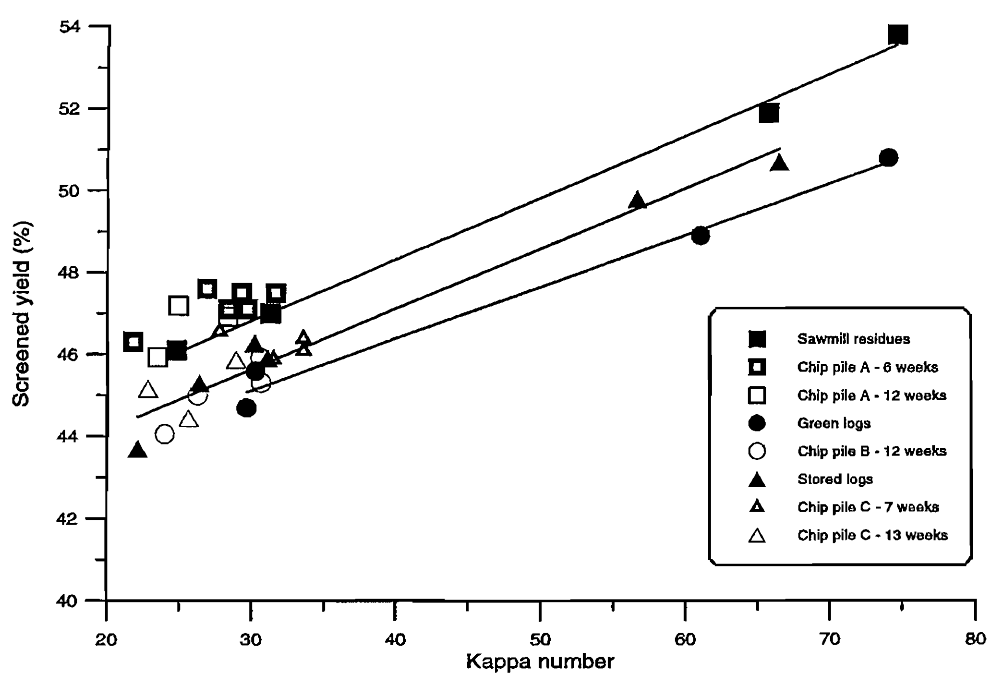
There was considerable variation in the density of the wood samples, making it difficult to distinguish trends. Much of this variation would result from differences in the origin of the trees in the Beerburrum log storage facility. Even trees from a single location and age class can have considerable between-tree and within-tree variation, making it hard to obtain a reproducible sample from a large chip pile.

Despite the variation in the results, it was clear that the sawmill residues had a higher density than wood from whole logs, probably because the residues predominantly come from the outside of the log where fibres have thicker walls. After 6-weeks storage, there was some indication of a decrease in wood density, at least in piles A and B. The difference between the samples taken after 6- and 12-weeks storage was not statistically significant.

Pulping properties

White rot enzymes attack wood components including cellulose, so that severe attack has the potential to lower kraft pulp yield. One report on the effect of white rot in lodgepole pine indicated that kraft pulp yield decreased by 2.4 percentage points. In other tree species pulp yield losses were greater, and it was suggested that the effect of decay would vary with wood durability, time and environmental conditions (Hunt 1978). The progress and distribution of decay in the *Pinus elliottii* stored logs was by no means uniform, being patchy and confined to the sapwood area only.

Figure 1 - Kraft pulping properties



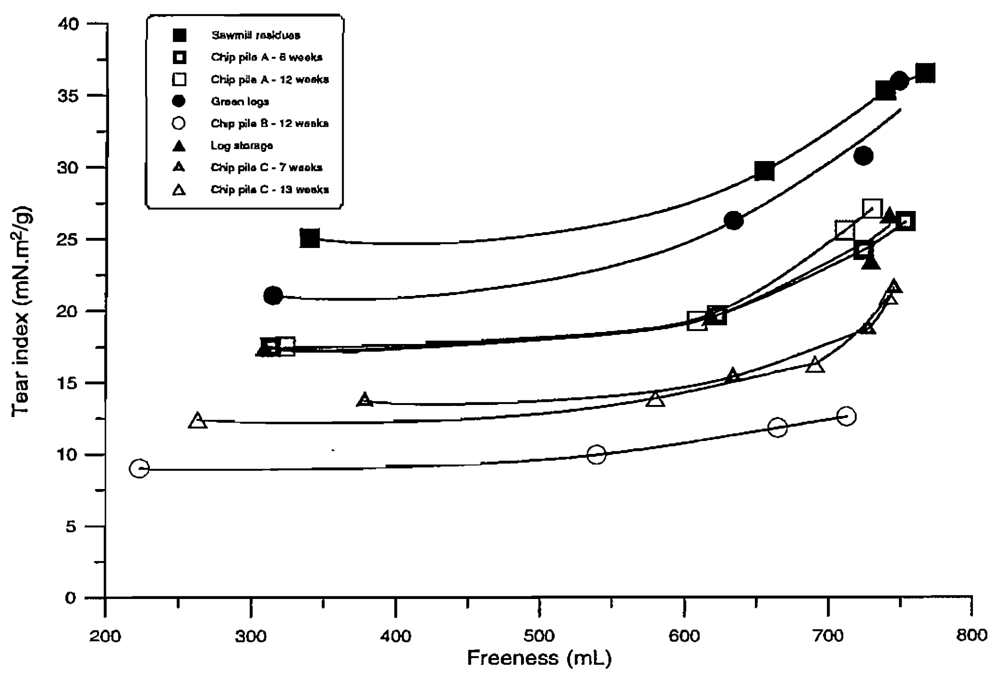
The kraft pulping properties of the *Pinus elliottii* wood samples are illustrated in Figure 1, where screened kraft pulp yield is plotted against Kappa number, a measure of the degree of delignification of pulp. It is usual to compare pulps at the same Kappa number, usually in the bleachable range. In this study, a Kappa number of about 30 was chosen.

The sawmill residues gave the highest kraft pulp yield, followed by the stored logs and the green logs. Since the fungus progresses from the outside towards the centre of a log, significant attack should have resulted in a decrease in pulp yield from the sawmill residues, because this material comes predominantly from the outside of the logs. These results give no indication of a decrease in pulp yield associated with the presence of the white rot fungus. Further, the pulping properties of the chips from the storage piles were similar or better than those of the corresponding freshly sampled material. The trend towards improved pulp yields in stored chips might have a biological cause, either from a change in the balance of lignin to carbohydrate, a reduction in pine resin content, or by an increase in wood porosity giving an improvement in pulping liquor penetration.

Papermaking properties

White rots systematically remove sugars from the reducing ends of the carbohydrate chains, meaning that the degree of polymerization of the carbohydrate chain is slowly reduced (Hunt 1978). If fungal attack is extensive, the potential exists for effects on pulp strength, particularly in tearing resistance. Figure 2 illustrates the relationship between tear index and freeness, a measure of the drainability of the pulp.

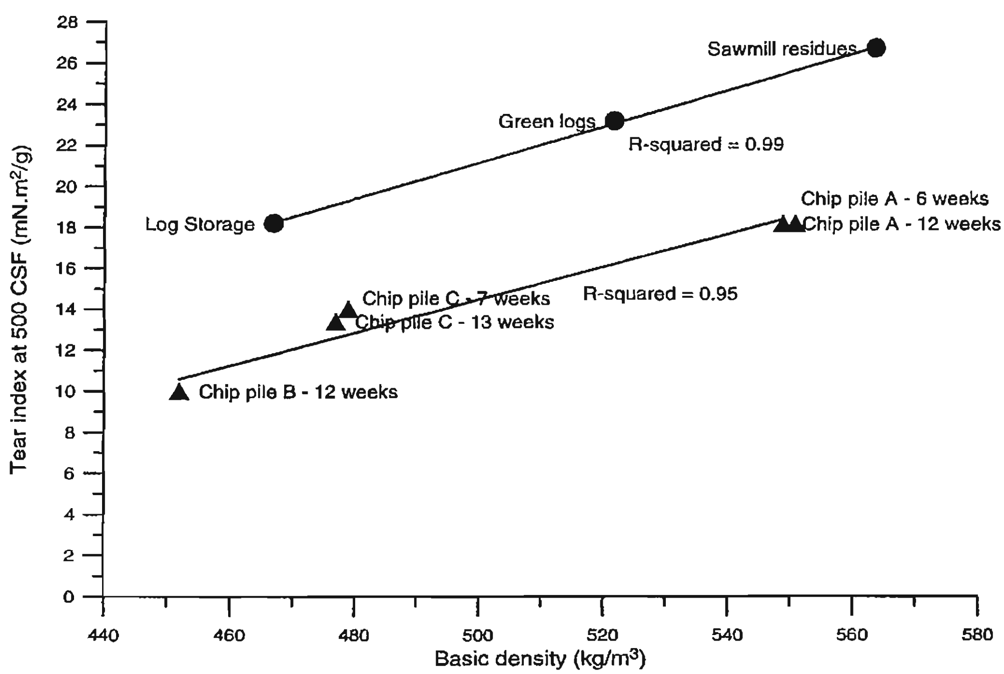
Figure 2 - Tear index vs freeness
***Pinus elliottii* kraft pulps at Kappa 30**



It is difficult to distinguish trends because of the variation in the data. However, the tearing resistance of kraft pulps prepared from sound wood is related principally to fibre length and fibre wall thickness (Watson *et al.* 1971). When fibre length is constant, most variation in tearing strength can be related to basic density, as basic density correlates well with fibre wall thickness. Thus those samples with high basic density may also be expected to have high tearing resistance, if all other factors are constant.

Figure 3 plots tearing resistance at a constant freeness against basic density for all the samples. Among the freshly obtained samples, a common relationship exists between basic density and tearing resistance, despite the differing origins of each wood sample. These pulps have higher tearing resistance than those prepared from the stored chips. Extending storage from 6 to 12 weeks caused little further reduction in tearing resistance. The decrease in pulp strength seems unlikely to be related to the presence of *Rigidoporus lineatus*, as the pulp prepared from the green chips exhibited a similar decrease in tearing resistance, and this pile had no fungus present.

Figure 3 - Tearing resistance vs basic density



CONCLUSION

There was some evidence of a small reduction in wood density in the chip piles on storage. The pulp yields from all samples of the stored chips were the same or higher than those of the corresponding fresh samples. Paper tearing resistance tended to decrease over the first six weeks of wood chip storage, but not thereafter. A similar decrease in tearing resistance in the pulp prepared from the green chip pile suggested that *Rigidoporus lineatus* was not the cause of the reduction in pulp strength.

ACKNOWLEDGMENTS

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STUDIES ON WOODCHIPS MADE FROM *Pinus* LOGS INFESTED WITH THE WHITE-ROT FUNGUS *Rigidoporus lineatus*

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ABSTRACT

In early 1996, the white-rot fungus *Rigidoporus lineatus* was found to be widespread in fire-salvage *Pinus* logs (predominantly *P. elliottii* var. *elliottii* plantation-grown to a saw-log-regime) being stored under water sprays in the Beerburrum Log-Storage Facility (LSF). When early consideration was being given to the utilisation of this material, it was obvious that woodchipping of sawmill residue and probably also of whole logs, was a strong possibility. A study was initiated to investigate the behaviour of *R. lineatus*-infested *Pinus* woodchips. Four small experimental piles were created on a sealed (bitumen) pavement at a woodchip export facility in Brisbane. These woodchip piles were created from (A) sawmill residues from 33- to 38-year-old sawlogs from the LSF, (B) freshly felled green logs from a 20-year-old pulp-wood plantation, (C) whole 33- to 38-year-old sawlogs from the LSF, and (D) a mixture of chips similar to those used in Piles B and C. Temperatures were monitored within the four piles and samples were collected for isolation for *R. lineatus* and for assessment of appearance, basic density, and moisture content from the new woodchips and from the piles after about 6- and 12-weeks storage. Some samples were taken after storage for pulping and papermaking studies (Clark *et al.* 1996).

The pile created from green-log woodchips exhibited high temperatures, apparently due to respiration of living parenchyma cell and of microorganisms, characteristic of activity on the soluble components of fresh woodchip material. There was no such obvious and marked heat generation within the piles of woodchip created wholly from LSF material while the pile of mixed woodchips produced an intermediate heating effect. Never-the-less, all piles showed some degree of on-going heat generation during 3 months of storage.

During storage for only 6 weeks, the woodchips from the LSF all lost the unpleasant, strong odour (volatile fatty acids and amines) associated with logs taken from under the Beerburrum sprinkler storage and during this time *R. lineatus* died out, either from microbial activity or from the elevated temperatures. It was concluded that the fungus would not cause further wood substance loss after removal of logs from the sprinkler storage and their conversion to woodchips. Even after 3 months in storage, there was no serious deterioration of woodchips in terms of appearance or basic density.

INTRODUCTION

In January 1996, it was discovered that the white-rot fungus *Rigidoporus lineatus* (Pers.) Ryvarden was causing decay of sprinkler-stored fire-salvage logs of *Pinus* spp.

(predominantly *P. elliottii* var. *elliottii*) in the Beerburrum LSF (Hood *et al.* 1996). It seemed probable that a considerable quantity of woodchip would be generated from these infested logs, either from sawmill offcuts, or from direct chipping of infested stored logs. Although it was expected that some of this woodchip would be used in local processing, it seemed likely that a large percentage would be exported. Export *Pinus* woodchip generated in the Beerburrum area of southeastern Queensland is transported by truck for storage at the woodchip export facility at Fishermans Island, Brisbane where it can be held storage for up to three months before shipment.

When this study was initiated, it was unclear how the presence of *R. lineatus* would influence the behaviour of woodchip; would it degrade the woodchip?, would it create different temperature profiles in the woodchip piles and in the holds of ships?, would the fungus be inactivated or killed by the high temperatures that were expected to develop within the piles?, or would the usual thermophilic (heat tolerant) micro-organisms which occur naturally within woodchip piles kill the *R. lineatus*?.

MATERIALS AND METHODS

Four different types of woodchip were used to create separate piles on a sealed bitumen pavement at the Fishermans Island woodchip storage facility. Three truck loads (nominally 80 m^3) of woodchip were used to create each storage pile with the chipping of the sawmill residues or logs and the establishment of each pile occurring over a 1- or 2-day period. The piles were more or less oval in shape (about 12 to 13 m by 13 to 14.5m), about 3m high, and contained an estimated dry weight of woodchips ranging from 37.6 to 41.1 tons.

The four piles were (A) part of a quantity of woodchips generated from sawmill offcuts of LSF fire-salvage butt-logs of select *Pinus* (predominantly slash pine; *P. elliottii* var. *elliottii*) from managed (thinned and pruned) 1956 to 1961 plantation; these were from a log pile with a low level of *R. lineatus* activity, (B) woodchips created by whole-log field-chipping of green, newly-felled, plantation logs from un-thinned, 1976 plantation purpose-grown for pulp production, (C) woodchips created by whole-log field-chipping of *Pinus* logs severely affected by *R. lineatus* from bays almost completely filled with fire-salvage top logs of from thinned and pruned 1972/1973 plantations, and (D) a quantity of mixed woodchips created by alternate whole-log field-chipping of *R. lineatus* infested LSF logs (as used for Pile C) and green pulpwood plantation logs (as used for Pile B). Pile D was included to represent the commercial environment where LSF chips would presumably have been mixed in with green-log chips.

Copper/constantan thermocouple cables were installed into the woodchip piles as they were being constructed. Probes were positioned at both the 1 and 2 metre level from the base of the pile. At each level one probe was positioned at about the centre of the pile with other probes at 1 m intervals to a distance of about 1 m from the outside of the pile (there were five probes at 1m and four at 2m). The thermocouple cables were terminated with plugs inside a polyurethane container (for weather protection) and temperatures within the piles were read periodically with a Kane-May KM45 meter.

A total of 10 woodchip samples were collected from each pile as it was being formed and subsequently five samples were taken from each pile, after it had stood for 6/7 and 12/13 weeks. To avoid completely destroying the piles, the 6/7-week samples were taken with a back-hoe, to allow access well into the pile but not right into the thermocouple cables. The samples within the woodchip pile were taken from several different positions, avoiding the outer layer. Final samples were taken as the pile was broken up at the end of the study after storage for 12/13 weeks; this allowed sampling to the centre of the pile. These woodchip samples were used for assessment of woodchip appearance, for isolations for Basidiomycete fungi, and for moisture and basic density determinations. Separate collections were taken from selected piles at the 6/7 and 12/13 week sampling for pulping studies (Clark *et al.* 1996).

Subsamples of at least 100 woodchips were taken from each of the samples. These were assessed for appearance as (W) white, apparently unaffected woodchips, (G) green-coloured woodchips due to invasion by the mould fungus *Trichoderma*, (O) orange colouration apparently associated with heart-woodchips, (WS) woodchips having a wet (water-soaked) appearance believed to be early invasion by *R. lineatus*, (B) woodchips showing varying degrees of the brown discolouration characteristic of advanced invasion by *R. lineatus*, and (S) woodchips with blue-stain (fungal) discolouration not related to *R. lineatus* invasion.

After initial isolation attempts, using whole woodchips, failed to detect *R. lineatus*, an alternative isolation procedure was used for isolations from Piles A and C (wholly created from LSF logs) after 6/7 and 12/13 weeks. In this procedure, individual woodchips were dipped in 100% ethanol and flamed; sterilised forceps were used to expose inner wood tissue; three or four small slivers of the inner wood tissue were plated onto Benomyl Malt Agar; plates were wrapped individually in parafilm, sealed in plastic bags and incubated; growth was assessed after 7 days and subsequently checked for up to 30 days for slow-growing isolates. To confirm the validity of this procedure, isolations were made from separate collections of woodchips from LSF sawmill offcuts and from whole-log chipping of severely affected LSF logs; these samples were similar to the LSF woodchips used to create Piles A, C and D.

Moisture content and oven dry unextracted basic density ($kg.m^{-3}$) were measured on all the woodchip samples (new woodchips, and after 6/7 and 12/13 weeks storage for each pile). All woodchip basic density determinations by DPI Timber Research for this project were based on procedures detailed in Australian Standard AS1301-1979, modified to exclude pre-soaking and towelling of the woodchip samples.

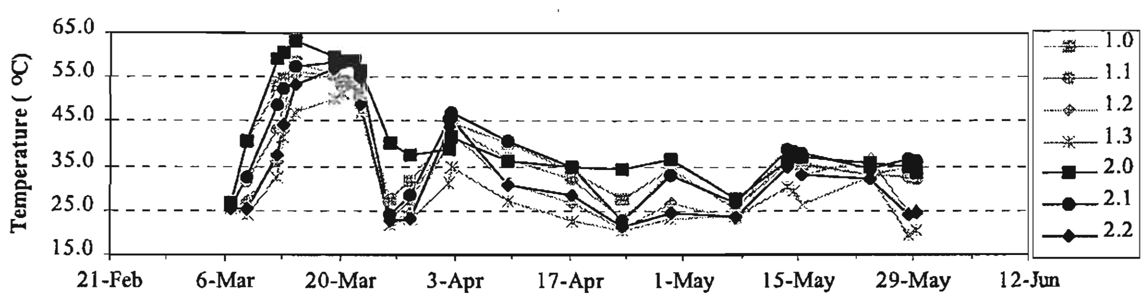
Because the woodchip piles were from different sources, not from the same 'population' of trees, a combined analysis of variance did not seem appropriate. Thus, apart from an initial analysis to compare the new woodchips, subsequent analyses to investigate basic density changes within the piles of stored woodchips were handled for the individual piles. These results were analysed using single classification analyses of variance for equal or unequal sample sizes as appropriate and differences between the range of means in each analysis were tested using the Student-Newman-Keuls Test for equal or unequal sample sizes as appropriate (Sokal & Rohlf 1969).

RESULTS

The four piles were established between 21st February, and 19th March 1996, with final harvests occurring between 15th May and 11th June. During that period there was a week of very heavy rainfall in Brisbane (606 mm at the Brisbane Airport, across the river from Fishermans Island, from 1st to 7th May). Temperatures were taken from within recognisable hot-spots on the top of the commercial *Pinus* woodchip pile at Fishermans Island on five occasions from early April to mid-June. During this period, the highest recordings at a number of positions were between 59° and 65°C. However, the heavy rainfall of early May caused a marked temperature fall even on this large woodchip pile.

Temperatures within the four study piles were recorded periodically over the duration of the study. Over the first week following its formation, each pile showed a temperature increase, however, Pile B (Figure 1a. - woodchips from newly felled logs) showed the greatest increase, reaching a high of 63.4°C. The two piles created wholly from LSF material showed smaller early temperature increases, attaining 42.7°C (Pile A - LSF off-cuts) and 41.1°C (Pile C- whole LSF logs; Figure 1b). Pile D (mixed LSF and freshly-felled pulpwood logs) showed an intermediate, but still marked, early temperature increase, with the maximum temperature rising to 49°C. After the early increases, the temperatures within all four piles declined over the following few weeks. Thereafter, apart from temporary temperature declines associated with the heavy rainfall in early May, as had been observed in the commercial pile, all four piles maintained inner temperatures within the range of 25° to 35°C over the remainder of their 3-month life.

1a. Pile B - Inner temperatures in pile of woodchips from newly felled pulpwood logs (Lot 10 - Bribie Road) 6/3/96



1b. Pile C - Inner temperatures in pile of woodchips from field chipping of whole LSF logs 12/3 & 13/3/96

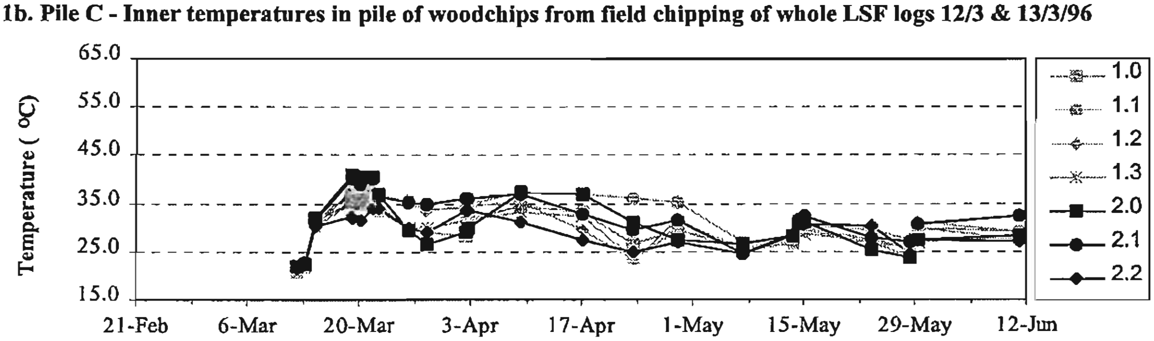


Figure 1. Inner temperatures in the two of the four experimental woodchip-piles.

Within each of the piles, there was generally an increasing temperature gradient from the probes near the outside of the pile to the probes at the middle positions. At the same time, the highest temperatures were at the 2 m level, presumably as result of thermal convection within the pile.

Initially the three woodchip piles containing material from the LSF (A, C, and D) all exhibited the characteristic, strong, unpleasant odour (apparently caused by volatile fatty acids and volatile fatty amines - Michael Kennedy *pers. com.*) associated with *Pinus* logs from the logstore. When these three piles were opened for sampling after the 6/7- and then 12/13-week storage period, there was none of this smell present. Except for the mould *Trichoderma* on woodchips in the pile from newly felled logs, and on woodchips from the mixed woodchip pile, and an orange colouration on heartwood material in whole-log piles, there was no indication of fungal (particularly *R. lineatus*) growth on any of the woodchips.

Samples of woodchips from each of the piles were visually examined at the start of each pile and then after 6/7 and 12/13 weeks of storage with the results summarised in Figure 2. Because of inexperience in the early stages of this study, there was no assessment of 'water-soaked' woodchips at the initial sampling of Pile A (sawmill offcuts). In that case, the 'white' category for week 0 for Pile A would represent the sum of 'white' and 'water-soaked' woodchips going into that pile. Another problem that occurred in assessing the appearance of the stored woodchips was the fact that the heavy rainfall of early May re-wet the drying woodchips in all four piles between the 6/7- and 12/13-week samples. As a result, assessment of the 'water-soaked' component proved difficult for final harvests of the four piles.

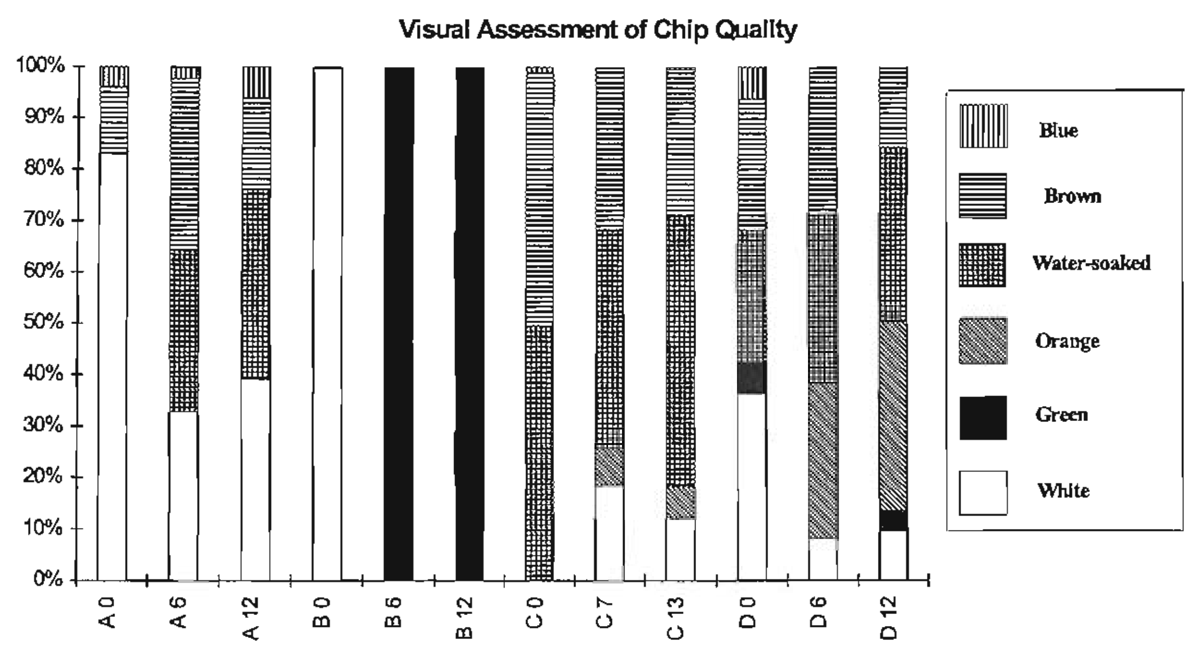


Figure 2. Appearance of four types of woodchips before (week 0) and after 6/7 and 12/13 weeks of storage. A = woodchips from sawmill residue; B. = woodchips from newly-felled pulpwood logs; C = woodchips from whole LSF logs; D = woodchips from mixed whole LSF and newly-felled pulpwood logs.

In Pile A (LSF sawmill off-cuts), although the 6-week sample may seem to suggest deterioration during storage with a decline in 'white' plus 'water-soaked' woodchips and a marked increase in brown woodchips, the results after 12 weeks strongly suggest that the 6-week result may have only been a sampling effect. This pile of woodchips contained a small percentage of blue-stained woodchips at all three sample dates. When Pile B (newly-felled pulpwood logs) was formed, all woodchips used for it were white. Over the next 6 weeks, all of the woodchips in this pile B turned 'green' due to the mould fungus *Trichoderma* which was also present after 12 weeks of storage. Bands of 'green' *Trichoderma* contaminated woodchips have been observed within the commercial pile at QCE during opening up during export operations. Nearly half of the 0-week woodchips in Pile C (whole LSF logs) were assessed as 'water-soaked' with almost all of the rest as 'brown'. However, the sample from this pile after 7 weeks of storage showed less 'brown' and some 'white' as well as a quantity of 'orange' woodchips not seen previously. There was little difference observed between the 7- and 13-week samples from this pile. Although *Trichoderma* contaminated woodchips were seen in Pile D (mixed green and LSF logs) when it was being sampled after 6 and 12 weeks, none were found in the five samples used to assess woodchip quality, and with the exception of the 'orange' woodchips at 6 and 12 weeks, there appeared to be little change in woodchip condition in this pile.

As mentioned above, the whole-chip isolation technique initially used in this study failed to detect any *R. lineatus*. Thus, extra samples of both off-cut and whole-log woodchips from other LSF material were used for isolation studies after the piles had been created, as well as isolations from Piles A (off-cut woodchips) and C (whole-log woodchips) after 6/7 and 12/13 weeks. Eleven percent of the extra samples of LSF off-cut woodchips yielded *R. lineatus* while the result from the extra samples of whole-log woodchips was 34%. There were no isolations of *R. lineatus* from either pile A or pile C after 6/7 and 12/13 weeks of storage.

The moisture content of all the new whole-log woodchips (Piles B, C and D) was high (Figure 3), being well over 100% as percentage of the oven-dry weight of woodchips. The whole LSF-log woodchips in Pile C were very wet with a mean moisture content of over 132%. In all four piles, the woodchips dried out somewhat during storage over the first 6/7 weeks, the sampling for which occurred during April for all of the piles. The final 12/13-week sampling for the piles occurred from mid-May until mid-June. As result of the heavy rainfall that occurred in early May, all four piles showed increases in moisture content of the woodchips at 12/13 weeks as compared to the 6/7-week samples. At the final samplings, there were obvious wet and drier zones within the piles associated with the input of water from the heavy rain. The extremely high moisture content of Pile D at 12 weeks (151%) was evident at sampling; the woodchips from that pile having a surface layer of free water.

There were significant differences in the basic densities of the new woodchips used for Pile A (sawmill offcuts) as compared to the other three study piles (Figure 4). The basic density results for Pile A (sawmill offcuts) and Pile B (newly-felled logs) showed no difference between the 0 and 6-week samples, but there were significantly lower values from both of these piles after 12 weeks storage. On the other hand, Pile C (whole LSF logs severely infested by *R. lineatus*) showed no difference in basic density at any sampling. Pile D (mixed LSF and freshly-felled pulpwood logs) showed significant decreases in basic density with storage for 6 weeks, and again for a further 6 weeks.

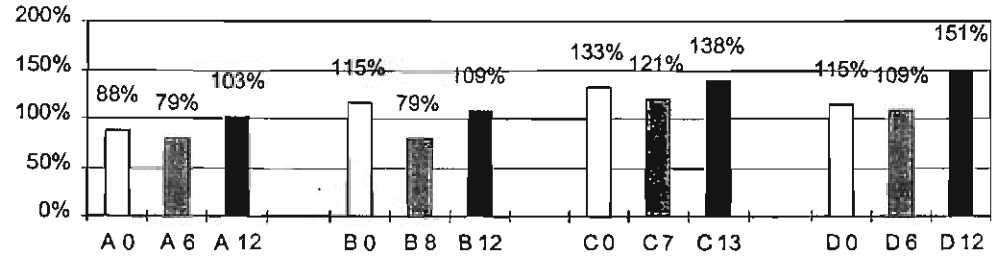


Figure 3. Moisture content on an oven-dry basis of woodchips before (week 0) and after 6/7 and 12/13 weeks of storage.
A = woodchips from sawmill residue; B = woodchips from newly-felled pulpwood logs; C = woodchips from whole LSF logs; D = woodchips from mixed whole LSF and newly-felled pulpwood logs

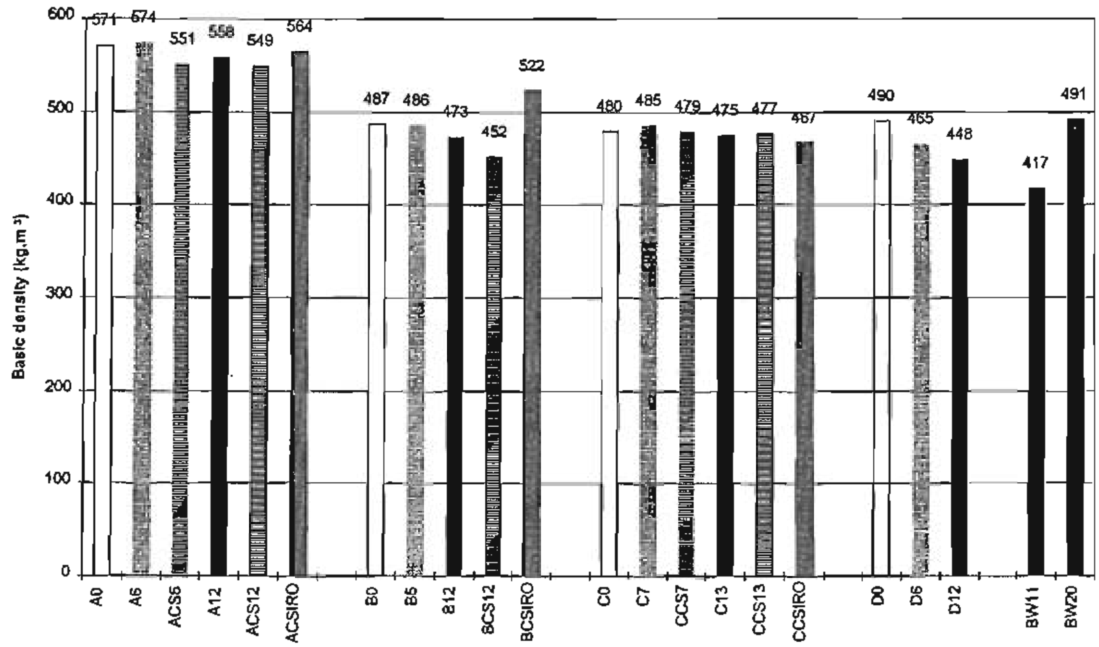


Figure 4. Comparison of basic densities of Pinus woodchips from current study, the CSIRO pulping study (Clark *et al.* 1996) and for 11- and 20-year-old trees from Beerwah (Watson *et al.* 1971).
A = woodchips from sawmill residue; B = woodchips from newly-felled pulpwood logs; C = woodchips from whole LSF logs; D = woodchips from mixed whole LSF and newly-felled pulpwood logs; 0 = fresh samples; 6/7 = stored for 6 or 7 weeks; 12/13 = stored for 12 or 13 weeks storage; CS = CSIRO results from storage piles; CSIRO = CSIRO composite of single-log samples (Clark *et al.* 1996); BW11 = 11-year-old trees from Beerwah (Watson *et al.* 1971); BW20 = 20-year-old trees from Beerwah (Watson *et al.* 1971).

The CSIRO results (Clark *et al.* 1996) for basic density of composite sawmill-log residue and for whole LSF logs were comparable to those from the equivalent woodchip-study pile. On the other hand, the basic density of the CSIRO composite sample for newly-felled logs at 522 kg.m^{-3} was considerably higher than the values from the pile of woodchips from newly-felled logs (Pile B) which started at about 486 kg.m^{-3} and after 12 weeks was 473 kg.m^{-3}. To help explain these differences, data from for logs from Beerwah plantations have also been compared in Figure 4.

All the woodchips from sawmill residues from LSF logs (A0, A6, ACS6, A12, ACS12, and ACSIRO) had similar basic densities in the range from about 550 to 574 $kg.m^{-3}$, and those woodchips from whole LSF logs (C0, C7, CCS7, C13, CCS13, and CCSIRO) had similar basic densities in the range 467 to 485 $kg.m^{-3}$, apparently reflecting the common origin of each type of woodchip. Although they all came from similar LSF logs, the higher values for the 'A' woodchips, as compared with the 'C' woodchips, arose because the 'A' woodchips, as sawmill residues, were entirely (ACSIRO) or largely (all other 'A' samples) from the outer, naturally denser portions of the logs whereas the 'C' woodchips were from whole logs, and thus contained a mixture of material from the outer, denser wood tissues to inner, less dense wood.

The woodchips from newly felled trees used for the CSIRO pulping study (BCSIRO) at 522 $kg.m^{-3}$ were considerably denser than the woodchips used for the storage study (B0, B6, B12, and BCS 12), the basic densities of which ranged from 452 to 487 $kg.m^{-3}$. This difference is apparently related to age of the trees used to produce the two types of woodchip; BCSIRO were produced from select, 35-year-old, trees from a managed (thinned and pruned) DPI Forestry saw-log plantation, compared with the younger, 20-year-old trees from a pulpwood planting from which the woodchips were generated from Pile B. The effect of age on woodchip basic density is illustrated by the data from Watson *et al.* (1971) for butt logs from non-select 11- and 20-year-old *Pinus elliottii* trees from managed plantations at Beerwah; butt logs containing denser wood than do the logs from higher up a tree.

The woodchips from Pile D (mixed LSF and newly-felled logs similar to those used for Pile B) showed more variability within samples, and results indicate a reduction in basic density during storage, as also occurred in Pile B, at least between 6 and 12 weeks. Whist the basic density figures for Pile A (sawmill residue) also suggested a change between 6 and 12 weeks, there was no such effect in Pile C (whole LSF logs). Some of the recorded decline in Pile D may be related to sampling problems arising from poor mixing that occurred as this pile was formed from alternate chipping of the two types of log.

DISCUSSION

During outside storage of pulpwood woodchips spontaneous heating within the woodchip pile is a normal occurrence (Springer & Hajny 1970; Tansey 1971; Feist, Springer & Hajny 1973; Hulme 1975; Hulme & Stranks 1976). This heating results from the respiration of living ray parenchyma cells in the wood, bacterial growth, direct chemical oxidation, and fungal growth (Feist, Springer & Hajny 1973). Hulme (1975) recognised three chronological heating phases which were ascribed to respiration by (1) wood cells, (2) colonizing microorganisms and (3) wood-destroying fungi with the main nutrients for 1 and 2 being simple nutrients and for 3 wood fibre; with serious wood fibre losses only beginning in the third heating phase when temperatures fall below 50°C. According to Kubler (1984) diffusion of oxygen, heat conduction and vapour diffusion play a role in self heating of all forest products, with convection of hot air, as in a chimney, transferring additional heat out of permeable materials such as open woodchip piles. Kubler (1984) indicated that heat generated by oxygen diffusing into the material is lost through conduction, and in moist material, through diffusing vapour; since heat losses increase more rapidly with temperature than does diffusion of oxygen, woody materials reach a stable temperature at which all heat that can be generated by the diffusing oxygen is lost. The 'high' temperatures attained within woodchip piles are such as to favour the growth of thermophilic bacteria, actinomycetes and fungi (ie., organisms that thrive at relative high temperatures (above 45°C)) (Greaves 1971, Tansey 1971; Hulme & Stranks 1976; Hoover-Litty & Hanlin 1985)

The temperature profiles obtained for the woodchips from newly-felled pulpwood logs (Figure 1a) showed a dramatic, early temperature rise within the inner zones of the pile. Maximum temperatures in this pile of between 55 and 65°C occurred between 7 and 14 days after the pile's formation with new green woodchips. Following a temperature fall, the inner parts of this pile maintained a temperature well above the outside daily average temperatures, except for the temporary decline associated with the heavy rains of early May. There was no marked early temperature rise in the woodchip piles formed wholly from LSF material (Figure 1b), while the mixed woodchip pile showed an intermediate temperature increase. The three piles with LSF material all maintained temperatures somewhat above the outside daily averages. Presumably the early marked temperature rises in Pile B, and the lesser rise in Pile D, represent the chronological phase 1 (respiration of wood cells) and perhaps phase 2 (respiration by colonizing microorganisms) of Hulme (1975); these phases being based on simple nutrients in the wood tissue. Such nutrients would have been low, or absent in the woodchips cut from LSF logs, hence the absence of such a dramatic temperature increase in Piles A and C.

There was a complete absence of the unpleasant odour, characteristic of LSF logs, after outside storage of woodchips for 6 weeks. This odour is believed to be due to volatile fatty acids and volatile fatty amines, and its disappearance in storage is possibly associated with the death of these organisms within the woodchip-storage piles and/or loss of the volatiles over time. Changes in the appearance of the woodchips in the various piles were difficult to assess, particularly as a result of the re-wetting associated with the heavy rainfall of early May. Over all, whilst there was some evidence of increasing discolouration of woodchips in the four piles, the most dramatic effect was the colonisation of woodchips in Pile B (newly-felled pulpwood logs) by *Trichoderma.*

The failure to isolate *R. lineatus* within the pure LSF woodchip piles after 6-weeks storage is likely to be due to competition by other organisms and possibly also the temperatures achieved within these piles. Temperatures within the piles created from infested LSF material did not exceed 45°C and although *R. lineatus* did not grow at temperatures exceeding 37°C in laboratory studies (Hood, *et al.* 1996), the fungus survived 1 but not 2 hours at 45°C (Powell 1996). The temperatures recorded in the mixed pile, most of which exceeded 35°C, were obviously more likely to have been lethal, particularly as they persisted for some days.

Moisture content of the woodchips cut from the LSF logs were very high, consistent with the storage of the logs under sprinklers, while the green-log woodchips were somewhat drier. The moisture contents all types of woodchip initially declined but increased again as result of the heavy rainfall in early May.

The basic density of the new woodchips reflected the source material with older, sawmill logs from the LSF being denser than the pulpwood-grown logs used in Pile B; the sawmill residue woodchips from the outside of the LSF logs were naturally denser than the woodchips from the whole LSF logs which contained the less dense inner log tissues as well as the denser outer log tissues. Within each type of woodchip, except for the whole LSF logs (Pile C), there was indication of deterioration over the 12/13-week storage period. However, apart from the pile of mixed woodchips (Pile D) where the losses after 6- and 12-weeks storage were 94.9% and 91.4% of the new woodchips respectively, the other decreases in basic density did not exceed 3% of the initial value.

This study indicated that woodchips created from the LSF logs invaded by the white rot fungus *R. lineatus* could be stored for at least 3 months without serious deterioration in terms of woodchip appearance and basic density. Losses in basic density, although statistically significant, were essentially of small proportions. The apparent disappearance of *R. lineatus* within the woodchip piles within 6 weeks of storage indicates that the fungus should not continue to cause wood substance loss once the logs are removed from the sprinkler storage system and the logs are converted into woodchips. In commercial practice, the innate heating of green *Pinus* woodchips could be used within large woodchip piles to create temperature levels high enough to guarantee the death of *R. lineatus* providing the infested woodchips were buried within ordinary woodchips (ie., not at the bottom or on the outside) of the pile.

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