Forest&Wood Products Australia

RESOURCE CHARACTERISATION & IMPROVEMENT

PROJECT NUMBER: PN07.3018

MAY 2008

Sorting plantation *Eucalyptus nitens* logs with acoustic wave velocity

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Publication: Sorting plantation *Eucalyptus nitens* logs with acoustic wave velocity

Project No: PN07.3018

ISBN: 978-1-920883-30-0

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Final report received by FWPA in April 2008

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Sorting plantation *Eucalyptus nitens* logs with acoustic wave velocity

Prepared for

Forest and Wood Products Australia

by

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Executive summary

Sawn lumber from plantation-grown *Eucalyptus nitens* displays significant variation in stiffness and strength. Diversion of low-strength material to non-structural timber production and separation of high strength material for premium value structural applications will improve resource utilisation and enterprise profitability. Acoustic wave velocity (AWV) was evaluated as a direct measure of wood stiffness using two age classes of *Eucalyptus nitens.* The two age-classes (8 years and 13-15 years) from a total of five sites provided material representative of the resource currently being directed to the structural market. Standing trees and felled logs were measured before and after harvest using readily available stress wave timing tools (FAKOPP and Hitman). Logs were sawn, dried and finished according to normal structural processing requirements. One sample board per log was then tested for stiffness, bending strength and hardness. Log samples were also collected to determine green and basic density, and relationships between the evaluated wood properties and AWV measurements in trees and logs were determined.

The AWV along logs provided the strongest correlation with wood stiffness facilitating the segregation of logs into stiffness classes. AWV cut-off values were identified to batch logs into three stiffness classes with an average MOE of 12, 10 and less than 10GPa. Although AWV measurement on logs provided the single best correlation with an R^2=0.54 (n=155), it was observed that both AWV on logs and trees provided highly significant positive correlation with board stiffness. The correlation between tree AWV and stiffness was sufficiently good (R^2=0.36, n=155) to allow trees to be batched to segregate the higher value structural material. One cut-off AWV was identified to batch material into two stiffness classes with an average MOE of 12 and 10GPa. Given that AWV and wood property values were significantly different among sites this study indicates that acoustic assessment of *E. nitens* plantations could provide some indication of the resource value for the structural market. A weaker but still highly significant positive correlation was found between stiffness and hardness indicating that segregation based on increasing stiffness would also improve hardness values.

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1 Introduction

Acoustic wave velocity (AWV) is one of a suite of non-destructive evaluation tools now available to the Australian sawn hardwood industry. Taken with wood density, AWV provides a direct indication of the dynamic MOE (Modulus of Elasticity) and the timber's stiffness (Carter, Briggs *et al*. 2005). It has been shown to be a good indicator of dry wood stiffness and has been successful in segregation of softwoods for structural timber production (Tsehaye, *et al* 1997, Ross 1999, Dickson and Matheson 1999). Dickson *et al.* (2003) used AWV tools to segregate sawlogs of *Eucalyptus dunnii*, reporting a significant relationship between AWV and timber stiffness. Ilic *et al.* (2005) used AWV to segregate eucalypt logs and study internal checking in sawn boards. This project will determine whether AWV can be successfully used to batch plantation grown *E. nitens* logs for improvement of structural grade out-turn, and suitable AWV cut-off values for such batching.

Sawn plantation-grown *Eucalyptus nitens* displays significant variation in stiffness and strength. Diversion of low-strength material to non-structural timber production and separation of high strength material for high value structural applications will improve resource utilisation and enterprise profitability. Benefits from AWV-assisted batching for structural applications can potentially extend to other eucalypt species grown in Australian plantations including *Corymbia* spp., *E. dunnii*, *E. globulus, E. grandis* and *E. pilularis*.

Plantation-grown *E. nitens* will comprise an increasing proportion of the future sawlogs produced in Tasmania, for both structural and appearance products. Forestry Tasmania has established over 20,000 ha of pruned *E. nitens* plantations intended for appearance-grade applications. These plantations will also yield unpruned upper logs potentially suited to structural products. Tens of thousands of ha of additional *E. nitens* plantations in Tasmania owned by FEA Ltd and other private companies are potentially available for sawing for structural products in the future. AWV therefore has potential to improve log allocation to appropriate processing streams for large volumes of sawlogs per year in Tasmania alone. AWV measurement is low-cost, so effective segregation to appropriate end use would be highly cost-effective.

2 Methodology

2.1 Harvest

2.1.1 Site

Sites were selected from FEA's plantation estate to provide two age classes (approximately 8 years to simulate thinning and 13-15 years to simulate clearfall). Three site productivity classifications were selected per age-class: high, medium and low site index. As the low productivity site from the age-class 8 trees didn't produce any sawlogs, a total of five sites were included in the study. Four sites were from North-east Tasmania and one from North-west. The variety of sites is expected to provide a broad range of material in terms of density and stiffness. **Table 1** provides a summary of the sites selected.

Table 1 Site numbering and colour coding

<table>
<tr><th></th><th>Site Classification</th><th>High</th><th>Medium</th><th>Low</th></tr>
<tr><td rowspan="6">Clearfall</td><td>Coupe</td><td>NE006B</td><td>NE011A</td><td>NE007B</td></tr>
<tr><td>SI* (initial estimate)</td><td>C</td><td>E</td><td>J</td></tr>
<tr><td>Date planted</td><td>11/93</td><td>11/91</td><td>9/93</td></tr>
<tr><td>Colour</td><td>Red</td><td>Orange</td><td>Yellow</td></tr>
<tr><td>Number of logs</td><td>31</td><td>36</td><td>29</td></tr>
<tr><td>Site number</td><td>1</td><td>2</td><td>3</td></tr>
<tr><td rowspan="6">Thinning</td><td>Coupe</td><td>NE026</td><td>NW007A</td><td rowspan="6">No sawlog</td></tr>
<tr><td>SI (initial estimate)</td><td>A</td><td>E</td></tr>
<tr><td>Date planted</td><td>12/98</td><td>12/98</td></tr>
<tr><td>Colour</td><td>Green</td><td>Blue</td></tr>
<tr><td>Number of logs</td><td>29</td><td>30</td></tr>
<tr><td>Site number</td><td>4</td><td>5</td></tr>
</table>

*SI = Site Index

The trees on each site were assessed and areas sufficient to recover approximately 30 sawlogs from a single plot were selected for harvest.

2.1.2 Pre-harvest assessment

All trees in the selected areas were assigned a 3-digit number with the first digit being the site number and the next two consecutive numbers from 01.

The stress wave velocity (SWV) of each sawlog tree was measured using the FAKOPP microsecond timer. Based on the prevailing wind direction as indicated by the wind rose from the nearest meteorological site, readings were taken on the western aspect of stem for the NW coupe and the north-western aspect for stems for NE coupes. The AWV was measured over a one metre length from 0.5 m to 1.5 m above ground level.

2.1.3 Harvest

The selected trees were harvested and debarked. Sawlogs were cut to a minimum of 5.55 m long. Stems were merchandised to maximise sawlog recovery. Where more than one sawlog was recovered per stem the sawlogs were numbered with a four integer code, i.e. the three integer tree code followed by a log sequence number e.g. 403/2.

Coloured tags were used to confirm the position of the log in the tree, i.e. butt, 2nd and 3rd log.

Each site was assigned a site colour with two shades. The small end of each log was painted the site colour. Half the logs were painted one shade, the other half the second shade. The large end of each log was sealed with clear log grease (Dussek-Campbell Technimul).

2.2 Mill operations

2.2.1 Mill measurements

The harvested logs were delivered to FEA's Bell Bay sawmill and laid out on bolsters (**Figure 1**). The large end of each log was then trimmed, and a 25 mm disk recovered (for measurement of density and green moisture content) to leave a 5.4m sawlog. The small and large end diameters of each log were then measured. The acoustic wave velocity of each log was assessed with the Hitman HM200 now known as the Director HM200.

Figure 1. Measuring logs from site 4

After assessment, the large end of each log was painted with one of 22 colours. Colour combinations were unique so milled boards can be traced to the source log, identifying the tree and sawlog position in the tree.

2.2.2 Properties measurement

Green and basic density measurements were made on a diametral strip from the 25 mm disk recovered from each log.

2.2.3 Log processing

Logs were allocated to diameter batches on FEA's scanner before milling to a cutting pattern according to diameter class (**Table 2**). Further detail on cutting patterns used is provided in Appendix 8.2.

Table 2. Cutting patterns by log diameter class

SED min	SED max	100x38	100x25	150x38	150x25
150	169	1	2		
170	179	2			
180	199	2			1
200	222	2		1	
223	270	2		2	

Figure 2 shows colour-coded boards in green packs after milling.

Figure 2. Boards in green packs after milling

2.2.4 Drying

All boards were racked and air-dried to below fibre saturation point on-site at FEA, over a period of four months (April – August 2007). Boards were then kiln-dried to final moisture content (12%) using FEA's standard schedule for structural *E. nitens*. Following drying the boards were planed to final dimensions.

2.2.5 Board assessment

Finished boards were sorted by site, log and position in the tree according to the colour-coding scheme used (**Figure 3**). The boards were visually strength graded by one of FEA's grading staff. One 38x100 sample board (from a maximum of two per log) was selected from each log and samples cut for in-grade testing of stiffness (MOE), strength (MOR), Janka hardness and oven-dry moisture content (MC). The board selected was "in-grade" (according to visual grading rules) where possible, otherwise the best quality board was selected. Given the size of logs and products cut, the radial position of the board in the log was not considered (in some instances there was only one sample board per log).

Figure 3. Sorting finished boards by site, log and position in tree.

Strength and Stiffness Evaluation (Figures 4 and 5)

An 1800mm piece was cut from the selected board from the butt end after end split had been removed, thus test pieces were selected from approximately equal heights in the tree (considering butt-logs, 2nd logs and 3rd logs as three separate classes). The 4-point bending tests were carried out at FEA's structural testing laboratory according to AS/NZS 4063:1992. MOE and MOR were calculated and corrected to values at 12% MC based on the oven-dry MC of each sample by adjusting bending strength and stiffness according to AS 2878 (Standards Australia 2000).

Figure 4: 1800mm sample pieces cut and strapped for strength and stiffness testing.

Figure 5. Strength and stiffness evaluation at FEA's structural testing laboratory.

- **Janka Hardness (Figure 66)**

  A 150mm piece was subsequently cut from the butt end of the remaining sample board. This piece was tested at 2 points using an Instron machine as described by Mack (1979). Once hardness had been assessed the sample piece was oven dried and moisture content determined according to AS/NZS 1080.1 (Standards Australia 1997).

Figure 6. Janka hardness testing using an instron machine.

3 Analyses

Tree-AWV, Log-AWV, stiffness, strength, hardness, green density, basic density were tabulated with relevant tree and log measurements and correlations between the traits determined. Data were grouped and analysed by individual site, by age class and then pooled and analysed as one dataset. Pearson's product-moment correlation coefficients "r" (a common measure of correlation between two variables) were calculated amongst variables for each grouping. Linear regression equations were determined for predicting stiffness from DBH, tree AWV, log AWV and green density. The correlation between AWV and stiffness was analysed further to determine what batching values could be determined from the results. The butt-log MOE (and AWV) was tested against upper log MOE and AWV using Students T-Test to determine whether there was any significant difference. Data for 155 logs was tabulated, with 139 butt-logs, 13 2^{nd} logs and 3 top logs.

4 Results and discussion

4.1 Wood Properties

The data for individual tree, log and board measurements for each site are provided in Appendix 8.3. A summary of mean wood properties including tree and log measurements is provided in **Table 3**. The standard error is provided to measure the error in the prediction of green density, basic density, MOE, MOR and janka hardness from tree and log AWV. It should be clear that the standard error measures, not the standard deviation of the estimate itself, but the standard deviation of the error in the estimate.

Table 3. Mean tree and log data

				Green Density (kg/m3)			Basic Density (kg/m3)			MOE (GPa)			MOR (MPa)			Janka Hardness (kN)		
	Mean			Standard Error		Mean	Standard Error		Mean	Standard Error		Mean	Standard Error		Mean	Standard Error		Mean
	DBH (cm)	Tree Fakopp AWV (Km/s)	Log Hitman AWV (Km/s)	Tree AWV	Log AWV		Tree AWV	Log AWV		Tree AWV	Log AWV		Tree AWV	Log AWV		Tree AWV	Log AWV	
SITE 1	301	3.677	3.880	117	122	915	35	28	482	2.15	1.83	12.218	14.66	14.59	53.907	0.73	0.55	4.009
SITE 2	321	3.850	3.972	66	56	979	33	33	511	1.99	1.65	12.299	15.36	14.71	56.978	0.80	0.78	4.523
SITE 3	243	3.564	3.617	37	39	950	25	26	482	0.98	0.94	10.237	12.24	12.80	55.385	0.85	0.86	4.655
SITE 4	239	3.450	3.472	59	57	853	25	25	456	1.49	1.23	8.660	13.97	13.93	39.129	0.95	0.98	4.345
SITE 5	255	3.401	3.220	42	41	1044	30	30	460	1.30	1.18	9.410	14.29	14.10	51.359	0.68	0.67	3.708
AGE CLASS 13 (SITE 1-3)	291	3.708	3.835	83	86	949	32	31	493	1.79	1.52	11.650	14.08	14.12	55.505	0.84	0.84	4.394
AGE CLASS 8 (SITE 4+5)	247	3.425	3.344	108	87	954	28	27	458	1.82	1.41	9.042	15.15	15.11	45.348	0.89	0.86	4.021
ALL SITES	274	3.600	3.648	94	93	951	31	30	480	1.80	1.53	10.657	14.93	14.83	51.639	0.86	0.85	4.251

A comparison of tree and wood property data for each age class, indicate that, overall, the more mature wood (age class 13-15 years) was superior to the wood sawn from the 8 year old trees. Logs from the 13-15 yr old trees were larger than those from the 8 year old age class with the exception of site 5 (8 years old) that produced logs of larger diameter than the low productivity coupe (site 3) from the 13-15 year age class trees. Site 2 produced the best trees, having the largest diameter, highest mean basic density, MOE, MOR and second-highest hardness. Site 4 produced the smallest diameter trees, and had lowest basic density, MOE and MOR, although it performed relatively well in hardness. Wood from the 13 yr old trees had a higher average stiffness than the 8 yr old trees, approximately 2.5 GPa higher. The 13 yr old trees also had a higher average MOR (by approximately 10 MPa), a higher basic density (8% higher), and were harder than the 8 yr old trees by approximately 0.4 kN. MOR was largely dictated by visual grading done, i.e. only in-grade sample boards were property tested (where available).

A fixed effects model testing the effect of site (as a factor) and DBH (as a covariate) on the dependent variables (tree Fakopp, log Hitman, green density, basic density, MOE, MOR and Janka hardness) was carried out on butt-logs only (inclusion of upper logs would confound the effect of site). Site effect is significant ($P<0.001$) for all the variates, i.e. AWV measurements and wood properties among sites were significantly different, indicating the potential of AWV measurements to assess wood quality in forest stands. The data was also analysed according to age-class (lower logs only) with age as the single fixed factor. Analysed in this manner, age is highly significant ($P<0.001$) for all response variates except hardness where it is still significant with

P=0.026. Density, stiffness, strength and hardness are statistically greater in the older wood. A third model was used to analyse age and site within age as fixed effects. Both terms are significant (most are highly significant P<0.001) showing that wood properties differ between ages and sites within age-classes also differ. The means and probability values for the variables analysed are given in Appendix 8.4.

The standard error values in **Table 3**, are generally larger when tree AWV is the independent variable, than when log AWV is used, i.e. log AWV is generally the better predictor of green density, basic density, MOE, MOR and Janka hardness. The ability of tree and log AWV to predict stiffness is further discussed in section 4.2 statistical correlations.

4.2 Statistical Correlations

Correlations amongst variables (Table 4)) show in a general sense that more variables provided significant correlation in the older trees (age class 13-15), than the younger age 8 trees. For example, tree AWV was found to be significantly positively correlated with all variables (with the exception of DBH that had no significant correlation) for the older trees, whilst for younger trees, tree AWV was only significantly negatively correlated with DBH and positively correlated with log AWV.

In the pooled data correlations generally improved over the correlations observed at the age class level. DBH was significantly (positively) correlated with both tree and log AWV's, basic density, stiffness and strength. It appears that DBH is negatively correlated with tree and log AWV within an age class but positively correlated when the data is pooled. As there is little overlap of DBH values between age-classes (younger trees are generally smaller) it is possible to find a negative correlation within an age class, but a positive correlation when the data is pooled (plots are shown in the Appendix 8.5. In a study of *E. dunnii* logs Dickson et al. (2003) observed a significant negative relationship between log AWV and DBH (but no correlation with tree AWV) for age 9 trees. The authors of that study also observed no significant relationship between tree or log AWV and DBH for the 25 yr old trees. In agreement with the trends observed by Dickson et al (2003) log and tree AWV was significantly positively correlated with basic density, hardness, stiffness and strength. A weaker but significant negative correlation was also observed with log AWV and green density but not for tree AWV and green density. Basic density was significantly positively correlated with hardness, stiffness and strength in addition to DBH, tree and log AWV's. Hardness was significantly correlated with stiffness, strength, tree and log velocities. Stiffness was positively correlated with DBH, tree and log AWV's, basic density, hardness and strength.

Table 4 Pearson's correlation coefficients for each age class and pooled data for key variables.

Sites 1-3 (Age class 13-15)

	DBH	Tree Fakopp velocity	Log Hitman velocity	Green Density	Basic Density	Hardness	Stiffness (MOE)
Tree Fakopp velocity	-0.05						
Log Hitman velocity	-0.05	0.68					
Green Density	-0.13	0.27	-0.06				
Basic Density	0.14	0.53	0.56	0.17			
Hardness	-0.09	0.27	0.25	0.02	0.59		
Stiffness (MOE)	0.29	0.51	0.68	-0.06	0.40	0.27	
Strength (MOR)	0.02	0.28	0.27	-0.12	0.17	0.23	0.59

Sites 4&5 (Age class 8yrs)

	DBH	Tree Fakopp velocity	Log Hitman velocity	Green Density	Basic Density	Hardness	Stiffness (MOE)
Tree Fakopp velocity	-0.26						
Log Hitman velocity	-0.41	0.64					
Green Density	0.34	-0.17	-0.61				
Basic Density	0.00	0.15	0.19	0.16			
Hardness	-0.14	-0.05	0.24	-0.29	0.15		
Stiffness (MOE)	-0.06	0.18	0.27	0.28	0.20	0.16	
Strength (MOR)	0.19	-0.11	-0.14	0.35	-0.06	0.06	0.62

Sites 1-5 (Pooled Data)

	DBH	Tree Fakopp velocity	Log Hitman velocity	Green Density	Basic Density	Hardness	Stiffness (MOE)
Tree Fakopp velocity	0.17						
Log Hitman velocity	0.37	0.78					
Green Density	-0.02	0.08	-0.20				
Basic Density	0.29	0.57	0.61	0.13			
Hardness	0.01	0.25	0.32	-0.11	0.49		
Stiffness (MOE)	0.42	0.60	0.73	0.03	0.51	0.30	
Strength (MOR)	0.19	0.29	0.31	0.07	0.22	0.22	0.64

$P < 0.01$. (dark shading)
$P < 0.05$. (light shading)

In the 13-15 year age-class trees (and pooled data) stiffness was significantly correlated with both tree and log AWV's with the strongest correlations being with log Hitman velocity. Similar results were reported by Dickson et al. (2003) for *Eucalyptus dunnii*. One difference between the two studies is that for the younger age 8 trees we find stiffness to be significantly correlated with the log AWV (albeit weakly, r = 0.27), but not with standing tree AWV, whereas Dickson *et al.* (2003) report significant correlations (tree and log AWV) for both age class 9 and 25 yr old *E. dunnii*). Again, this indicates that the younger aged *E. nitens* trees in this study provide poorer correlations amongst MOE and other key wood properties. The reason for this is unclear, however, one feasible explanation could be that there is greater radial variation (of wood properties) in the younger trees; i.e. wood formed later is more uniform so that as the tree grows the more variable "core-wood" forms a lower proportion of the tree. Thus, log AWV (measuring an average MOE) may be closer to the individual piece MOE in older trees, but less reliable in the more variable younger trees. Considering that dynamic MOE = density x AWV^2 (Wang et al., 2001), the correlation between AWV^2 and stiffness was also examined, however, no improvement in the correlations was observed.

As expected, stiffness was significantly correlated with bending strength for all datasets. Pearson's correlations for tree AWV against stiffness were also tested for Butt logs only and for upper (2nd and 3rd) logs only to examine how tree AWV (measured at 0.5 to 1.5m) predicts stiffness along the length of the stem. **Table 5** shows that there is little difference in the correlation between butt logs only and the upper logs, i.e. tree AWV appears to be an equally good predictor of stiffness further up the stem.

Table 5. Pearson's correlation coefficients for Tree Fakopp velocity and stiffness for butt and upper logs

	Tree Fakopp Velocity All Logs	Tree Fakopp Velocity Butt log only	Tree Fakopp Velocity 2nd and 3rd log only
Stiffness (MOE)	0.60	0.58	0.55

P < 0.01.

P < 0.05.

Paired t-tests were conducted on a sub-set of data (excluding all trees with only butt log samples) comparing log AWV and wood property values for the butt-log against values for the second log. Table 6 shows that Log AWV, MOR and green density were significantly different, basic density was almost significantly different, but no significant difference was observed for MOE and hardness of butt-logs versus the second log.

The value of this result may be limited by the small sample size of upper-log material but the finding is included for interest. It may be harder to demonstrate a statistical difference between MOE than a difference in log AWV as we only tested one board per log. Testing multiple boards per log (were possible) may have helped detect a significant difference in MOE between butt-logs and second logs.

Table 6. Results of paired t-tests comparing log AWV and wood property values for butt-logs versus second logs.

	Butt Log Hitman	2nd Log Hitman	Butt Log Green Density	2nd Log Green Density	Butt Log Basic Density	2nd Log Basic Density	Butt Log MOE	2nd Log MOE	Butt Log MOR	2nd Log MOR	Butt Log Hardness	2nd Log Hardness
Mean	3.8	4.0	967.5	881.2	480.1	498.6	11.9	12.7	49.8	62.3	4.1	4.4
P(T<=t) two-tail	0.005		0.038		0.051		0.227		0.048		0.146	

P < 0.01

P < 0.05

Regression equations (**Table 7**) for predicting stiffness from tree AWV, log AWV, DBH and green density indicate that the best single variable for predicting stiffness is log AWV, accounting for 54% of the variation in stiffness in the pooled data. When examined at the age class level log AWV accounted for 47% of stiffness variation in age class 13-15 logs, but only 7% of the variation in age class 8 logs. Thus indicating that log AWV is a good predictor of stiffness in older trees but provides a poorer prediction for the younger trees examined in this study.

The addition of other variables that can be easily measured on trees or logs was explored. The addition of DBH or Green Density to tree Fakopp or log Hitman velocity provided minimal improvement in the prediction of stiffness.

Table 7. Linear regression equations for predicting stiffness from readily measured variables.

Age Class 13-15	
MOE = 8.2239 + 0.012 x DBH	R^2 = 0.09
MOE = -5.1466 + 4.5304 x tree Fakopp velocity	R^2 = 0.26
MOE = -9.7445 + 5.5786 x log Hitman velocity	R^2 = 0.47
MOE = 13.1342 -0.0016 x Green Density	R^2 = 0.00*
MOE = -9.4059 + 4.6723 x tree Fakopp velocity + 0.0128 x DBH	R^2 = 0.36
MOE = -10.4291 + 5.3054 x log Hitman velocity + 0.0059 x DBH	R^2 = 0.49
MOE = -2.4010 + 5.1730 x tree Fakopp velocity - 0.0054 x Green Density	R^2 = 0.31
MOE = -9.5156 + 5.647 x log Hitman velocity - 0.0005 x Green Density	R^2 = 0.47
Age Class 8	
MOE = 9.8083 - 0.0031 x DBH	R^2 = 0.00*
MOE = 4.1162 + 1.4380 x tree Fakopp velocity	R^2 = 0.03
MOE = 2.9913 + 1.8093 x log Hitman velocity	R^2 = 0.07
MOE = 5.4301 + 0.0037 x Green Density	R^2 = 0.08
MOE = 4.2993 + 1.4196 x tree Fakopp velocity - 0.0005 x DBH	R^2 = 0.03
MOE = 1.4931 + 1.9878 x log Hitman velocity + 0.0036 x DBH	R^2 = 0.08
MOE = -0.8729 + 1.7051 x tree Fakopp velocity - 0.0042 x Green Density	R^2 = 0.12
MOE = -13.7808 + 4.3406 x log Hitman velocity - 0.0087 x Green Density	R^2 = 0.31
Pooled Data	
MOE = 5.3404+0.0194 x DBH	R^2 = 0.18
MOE = -8.4965+5.3203 x tree Fakopp velocity	R^2 = 0.36
MOE = -7.1053+4.8689 x log Hitman velocity	R^2 = 0.54
MOE = 10.0470+0.0007 x Green Density	R^2 = 0.00*
MOE = -7.7434 + 4.4443 x log Hitman velocity + 0.0080 x DBH	R^2 = 0.56
MOE = -10.8715 + 4.8301 x tree fakopp velocity + 0.0151 x DBH	R^2 = 0.47
MOE = -12.1463 + 5.1334 x log Hitman velocity + 0.0043 x Green Density	R^2 = 0.57
MOE = -8.2650 + 5.3842 x tree Fakopp velocity - 0.0005 x Green Density	R^2 = 0.37

*R^2 value < 0.00

4.3 Using AWV to Batch Logs or Trees

4.3.1 Batching Logs

The procedure for monitoring stiffness in machine graded structural lumber, according to AS/NZS 4490-1997 (Standards Australia 1997[c]), is based on the *mean* MOE exceeding a specified characteristic value. Currently, Australian Standards do not require control of the variation around the mean MOE, however, this may change in the future. It is noted that some individual companies establish their own "in-house" verification rules, explicitly controlling the variation of MOE within each lumber grade. An excerpt from AS1720.1 (**Table 8**) shows the average MOE values for different MGP (machine graded pine) grades.

Table 8. Characteristic properties for MGP grades: AS1720.1-1997, Standards Australia 1997[b].

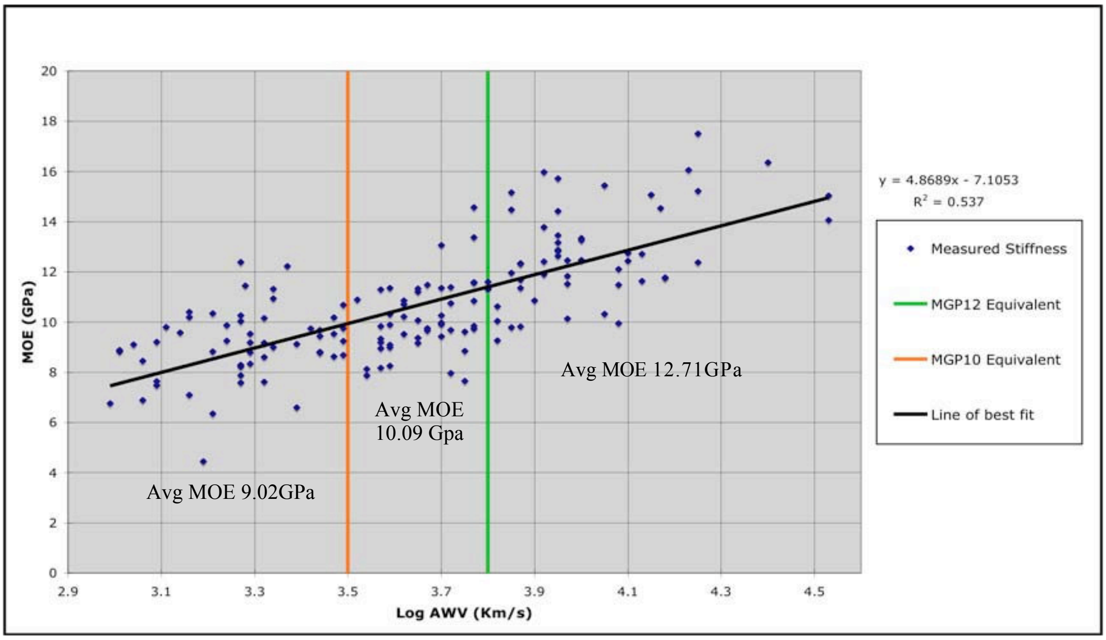
MGP grade	Characteristic strength, MPa				Short duration average modulus of elasticity parallel to the grain	Short duration average modulus of rigidity for beams
	Bending	Tension parallel to grain	Shear in beams	Compression parallel to grain		
	f'_b	f'_t	f'_s	f'_c	E	G
MGP 15	41	23	9.1	35	15 200	1 010
MGP 12	28	15	6.5	29	12 700	850
MGP 10	16†	8.0	5.0	24	10 000	670

* Properties apply only for 35 mm and 45 mm thicknesses.
† For 45 mm thickness, f'_b for MGP 10 may be taken as 19 MPa.
‡ The modulus of elasticity given has been obtained from bending tests and contains the effects of shear.

Two AWV cut-off values have been estimated from the observed results of this study to batch material into three grades with values (average MOE) aligning to recognised MGP grades (for comparative purposes).

Figure 7 shows the correlation between log AWV and board MOE, and indicates the AWV cut-off values.

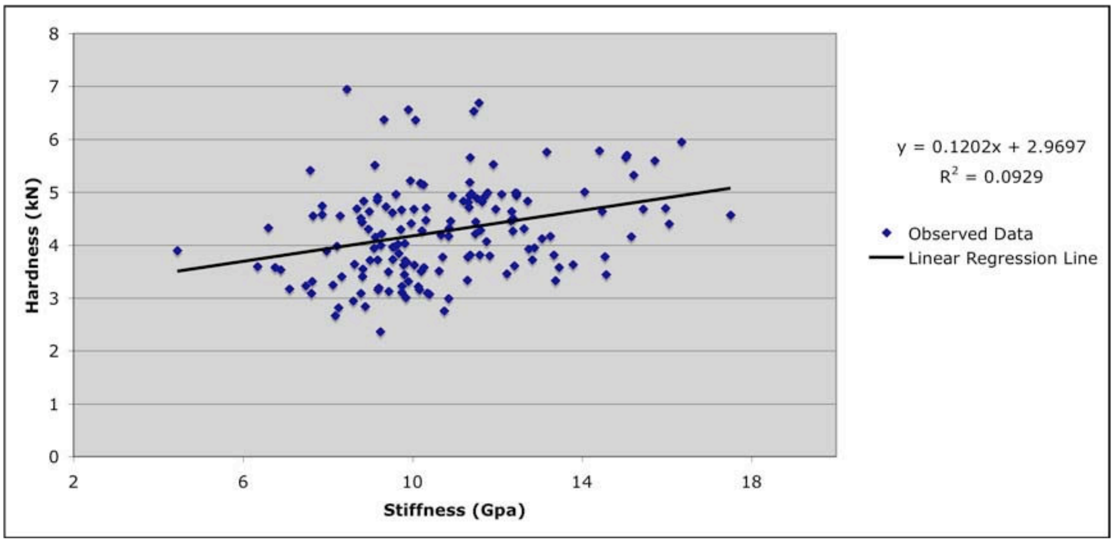
Figure 7. Correlation between log AWV and board MOE, with batching values indicated.



The mean MOE for logs with an AWV > 3.8Km/s (as identified by the MGP12 Equivalent line) is 12.71GPa. The mean MOE for logs with an AWV between 3.5Km/s (MGP10 Equivalent line) and 3.8Km/s is 10.09GPa. The mean MOE for logs with an AWV lower than 3.5Km/s is 9.02GPA. Thus, the observed results have been batched (according to AWV) identifying material that would attain the equivalent of MGP12, MGP10, and material that falls below MGP10. Identifying lumber falling below MGP10 equivalent is of interest, as the value of this material would be expected to drop off significantly.

Any sorting of logs to increase stiffness will also produce a correlated increase in wood hardness. Table 4 shows that there is a significant positive correlation between stiffness and hardness (r = 0.3). **Figure 8** further illustrates the relationship between these variables. Although the relationship is significant the relationship is much weaker than that reported by Dickson *et al* 2003 for *E. dunnii*, who observed r > 0.6.

Figure 8. Relationship between stiffness and hardness for pooled data.

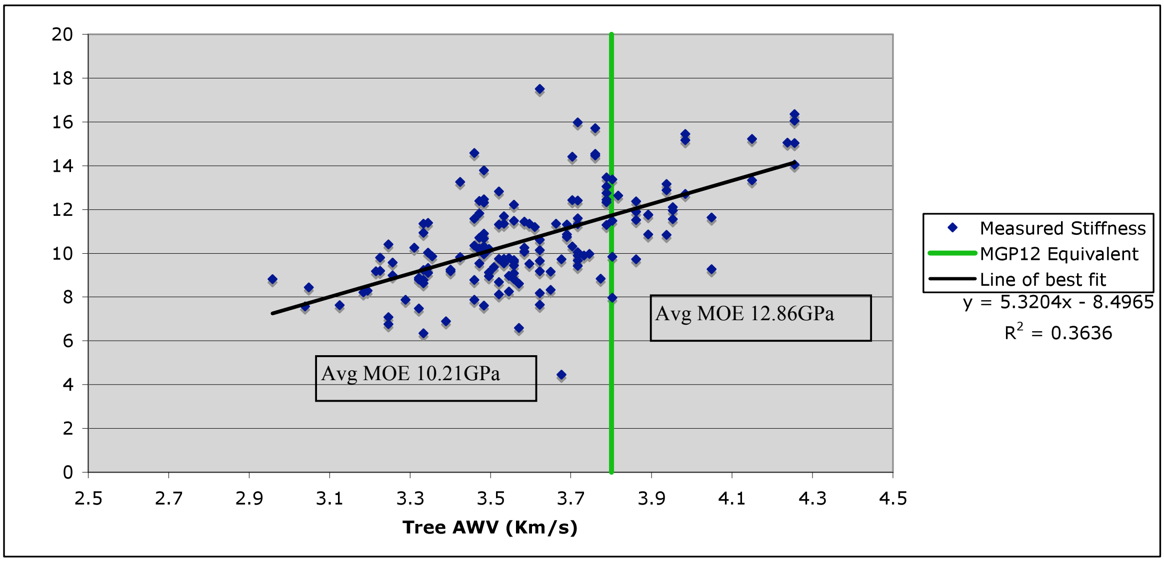


4.3.2 Batching Trees

Given the strength of the correlation between AWV measured on the standing trees and stiffness there is also batching potential at the tree level, albeit at a lower level than log batching. One AWV cut-off value was identified from the observed results of this study to batch material into two grades with values (mean MOE) aligning to recognised MGP grades (for comparative purposes).

Figure 9 shows the correlation between tree AWV and board MOE, and indicates the AWV cut-off values.

Figure 9. Correlation between tree AWV and board MOE, with batching values.



Trees with an AWV > 3.8Km/s (as identified by the MGP12 Equivalent line) have a mean MOE of 12.86GPa. Trees with an AWV less than or equal to 3.8Km/s have a mean MOE of 10.21GPa. Thus, the observed results have been batched (according to tree AWV) identifying material that would attain the equivalent of MGP12 and MGP10. Although the observed correlation between tree AWV and stiffness is not as good as that observed between log AWV and stiffness, **Figure 9** illustrates how tree AWV could be used to segregate high value structural material from lower quality material.

5 Conclusions

The objective of this study was to determine whether AWV could be successfully used to batch plantation grown *E. nitens* logs for improvement of structural grade out-turn. The results have been encouraging, with highly significant positive correlations being observed between log AWV, tree AWV and board stiffness.

In accordance with results published for other species, AWV along *E. nitens* logs was sufficiently well correlated with stiffness to enable logs to be batched to segregate material of varying stiffness. AWV cut-off values were identified from the results to batch the logs according to grades aligning with MGP grades. Logs were batched such that the resultant lumber was grouped into the equivalent of MGP12, MGP10, and those falling below MGP10. The correlation between tree AWV and stiffness was also sufficiently good to allow trees to be batched to segregate the higher value structural material. Given that AWV measurements and wood properties among sites were found to be significantly different, this study indicates that AWV measurements have potential application in the assessment of wood quality in *E. nitens* plantations, i.e. acoustic assessment of standing trees could provide indication of the resource value for structural markets.

Analyses of the data by age class suggested that older trees (13-15 yrs) provided much better correlations than younger trees, thus suggesting that a larger sample of the older trees could have improved the observed correlations. Reasons for the poor correlations in young trees are not clear, however, greater radial variation of MOE in young trees may offer a viable explanation.

Although the analysis was limited by sample size, upper logs had a higher AWV and produced significantly stronger (MOR) boards than butt logs from the same tree. However, no significant difference in MOE or hardness was observed between butt and upper logs.

6 Further work

Further work related to this study might investigate the radial and longitudinal modelling of stiffness in *E. nitens* logs with the aim of generating a 2-D stiffness profile from estimates of mean MOE. Such a study could be conducted on small clear samples investigating the AWV correlation with stiffness, and the radial and longitudinal variation of stiffness in the log. The occurrence of knots in the resource would likely limit correlation with MOR.

Another valid extension could be to investigate the use of AWV measurement on sawn *E. nitens* boards to facilitate mean board MOE grading rather than the use of a traditional roller type machine stress grader. Such methods are already common practice in NZ for radiata pine and are likely to be employed in Australia in the near future as grading standards develop.

7 References

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8 Appendices

8.1 Visual grading rules:

Permissible characteristics

The following characteristics shall be permitted within the limitations herein;

(a) *Knots (tight or loose, sound or unsound, intergrown or not, round, oval or arris, single or in a cluster) including occluded branch stubs, knot holes and holes other than those caused by insects.*

- (i) *width on wide faces of piece* – not exceeding one-third the width of the surface on which they occur
- (ii) *width on edges* – not limited
- (iii) *knot area ratio of bark-encased knots, loose knots or knot holes occurring within one-third of the board width of the edge*[1] – not exceeding 50%

(b) *Bark*

- (i) *width* – not exceeding 3 mm (measured radially)
- *(ii)* *aggregate length* – not exceeding one tenth of the length of the piece
- (iii) *extending from one surface of the piece to another* – not permitted.
- (iv) *area ratio of bark inclusions occurring within one-third of the board width of the edge*[1] – not exceeding 50%

(c) Decay or associated stain

- (i) *length* – not exceeding one-quarter of the length of the piece[2]

(d) Borer holes – as for knots

(e) Pith – no restriction

(f) End splits; aggregate length at each end – not exceeding the lesser of the width on the piece or 100 mm.

(g) Checks other than internal

- *(i)* *width* – not exceeding 3 mm
- *(ii)* *depth* – not extending from one side of the piece to the other
- *(iii)* *individual length* – not exceeding one quarter of the length of the piece

(h) Gum veins – as for checks other than internal

(i) *Internal checks* – not exceeding in aggregate a loss of one tenth of the cross-sectional area.

(j) Want, wane

- *(i)* not exceeding one tenth of the cross sectional area
- *(ii)* not exceeding one third of the width of the edge on which it occurs and not exceeding one half of the width of the face on which it occurs.

(k) Sapwood – not exceeding one-fifth of the cross sectional area at any cross section.

(l) Hit and miss

- *(i)* *within the limits for want and wane* – permitted
- *(ii)* *exceeding the limits for want and wane* – depth not exceeding 3 mm and individual length not exceeding 600 mm.

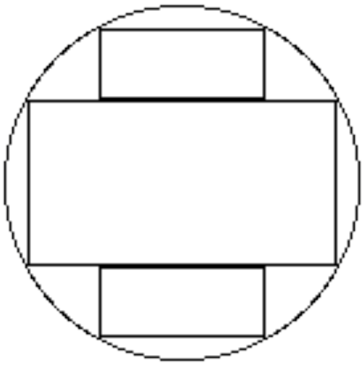
Combination of characteristics

A combination exists when two or more characteristics occur in a length of the piece such that there is less than twice the width of the piece between them, measured parallel to the length of the piece.

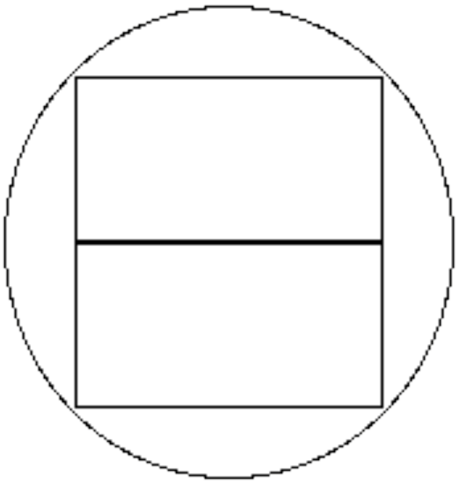
A combination of defects is permitted if the aggregate size of the combination is not greater than one characteristic of the maximum permitted size.

8.2 Cutting patterns used:

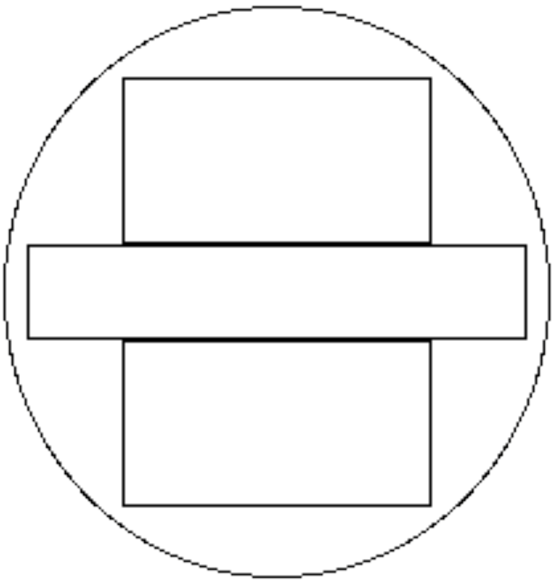
SED:150-169mm (2x25x100+1x38x100)



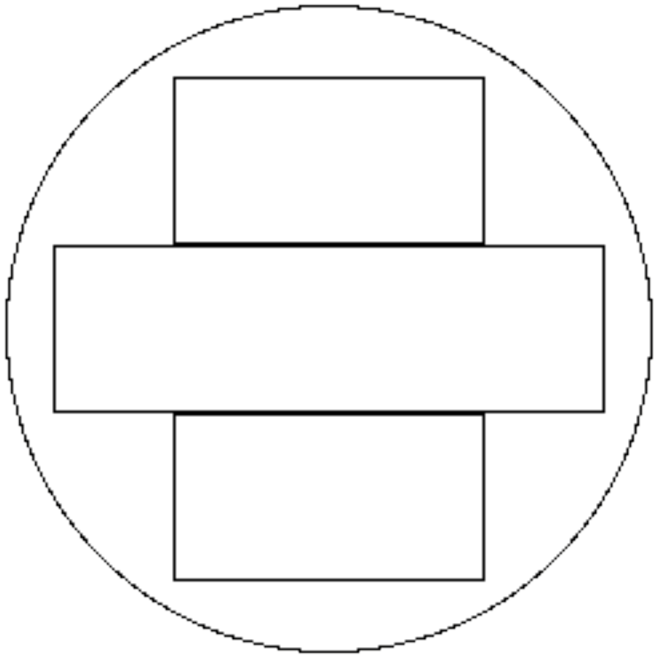
SED: 170-179mm (2x38x100)



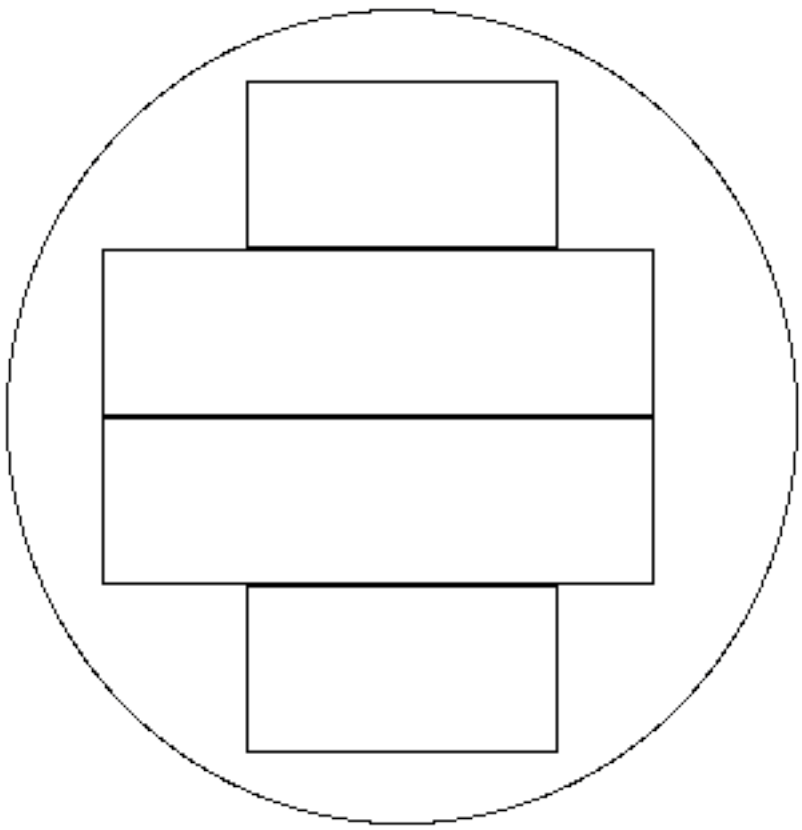
SED: 180-199mm (2x38x100+1x25x150)



SED: 200-222mm (2x38x100+1x38x150)



SED: 223-270mm (2x38x150+2x38x100)



8.3 Tree, log and board data:

		Log Data			Tree Data									Hardness	
Tree No.	Log No.	Hitman km/s	SED	LED	DBH	Height	Fakopp	Fakopp km/s	Green Density	Basic density	MC Average	MOE (GPA)	MOR (MPA)	Tangential KN	Visual Grading (1=in grade)
101	101	3.77	189	229	238	24.5	263	3.80	955.11	469.00	104%	13.372	67.92	3.332	0
102	102/1	3.77	205	242	260	26.1	263	3.80	982.94	467.94	110%	9.846	43.78	3.007	1
102	102/2	4.08	158	200	260			3.80	918.89	496.87	85%	11.485	48.18	4.444	1
103	103	3.82	154	197	205	23.6	276	3.62	916.76	443.79	107%	10.622	57.09	3.514	1
104	104	3.8	226	258	267	28.4	269	3.72	1027.65	512.47	101%	11.600	55.72	4.282	0
105	105/1	3.92	190	225	267	28.4	269	3.72	937.35	466.60	101%	12.407	51.68	3.608	0
105	105/2	3.92	145	185	267			3.72	914.15	523.16	75%	15.973	89.87	4.701	1
106	106/1	3.77	248	290	377	30	289	3.46	951.38	449.88	111%	14.572	61.94	3.447	0
106	106/2	3.77	201	247	377			3.46	499.00	499.00	69%	11.583	60.68	3.817	1
107	107	3.87	250	291	368	29.7	287	3.48	495.00	495.00	79%	12.315	62.03	4.466	0
108	108	4.08	198	250	368	29.7	287	3.48	1014.62	574.62	77%	9.950	19.12	5.220	1
109	109	3.85	238	292	291	27.3	251	3.98	1019.46	524.80	94%	15.163	63.01	4.161	1
110	110/1	4.05	198	238	291	27.3	251	3.98	973.63	498.80	95%	15.441	54.08	4.681	1
110	110/2	4.13	154	197	291			3.98	921.08	498.42	85%	12.713	51.34	4.837	1
111	111	3.92	263	306	400	30.5	287	3.48	933.66	457.14	104%	13.783	61.56	3.635	1
112	112	4	212	255	400	30.5	287	3.48	966.54	532.03	82%	12.462	56.06	4.985	1
113	113	3.72	185	222	234	24.8	271	3.69	964.55	459.34	110%	10.743	37.09	2.756	0
115	115	3.54	215	256	268	26.7	284	3.52	953.50	440.71	116%	8.122	17.12	3.251	1
116	116	3.95	170	213	268	26.7	284	3.52	887.54	462.68	92%	12.826	55.57	3.723	1
117	117	3.72	175	210	220	24.2	263	3.80	909.86	434.43	109%	7.968	44.10	3.891	0
118	118	3.49	280	317	360	32.1	300	3.33	905.26	445.50	103%	9.243	44.33	2.365	1
119	119	3.59	215	275	360	32.1	300	3.33	888.70	416.71	113%	11.357	58.88	3.812	0
120	120	4	225	288	288	27.3	241	4.15	956.28	486.76	96%	13.333	53.33	3.812	0
121	121	4.25	186	220	288	27.3	241	4.15	943.94	526.69	79%	15.222	64.74	5.329	1
122	122	3.67	277	305	351	29.3	283	3.53	837.18	413.81	102%	9.752	46.36	3.226	0
123	123	3.87	175	220	351	29.3	283	3.53	914.15	506.47	81%	11.683	52.64	4.913	1
125	125	3.62	236	325	323	27.5	288	3.47	1029.81	477.61	116%	10.707	33.05	3.777	0
126	126	3.97	198	234	323	27.5	288	3.47	885.34	471.36	88%	11.823	65.80	3.799	1
127	127/1	4.15	195	222	231	24.8	236	4.24	953.88	509.52	87%	15.061	88.09	5.703	0
128	128	3.97	210	230	277	28.3	276	3.62	1005.30	490.05	105%	10.134	54.16	3.218	1
129	129	4.25	160	200	277	28.3	276	3.62	892.09	487.60	83%	17.508	51.76	4.573	1
201	201/1	3.59	277	320	325	28	269	3.72	1020.61	459.95	122%	9.894	46.28	3.316	0
202	202	3.82	227	275	325	28	269	3.72	1034.85	529.18	96%	10.039	47.54	3.626	1
203	203	3.77	198	239	259	29.9	259	3.86	1042.22	501.74	108%	9.724	45.31	4.300	0
204	204	4.25	155	190	259	29.9	259	3.86	923.94	505.42	83%	12.369	56.26	4.265	1
205	205	4.23	251	279	295	28.6	235	4.26	996.04	521.28	91%	16.057	74.20	4.401	1
206	206/1	4.53	213	251	295	28.6	235	4.26	947.88	574.42	65%	15.027	83.53	5.659	1
206	206/2	4.53	178	214	295			4.26	865.83	568.63	52%	14.059	57.70	5.005	1
206	206/3	4.4	141	171	295			4.26	907.34	597.38	52%	16.351	94.88	5.951	1
207	207	3.57	288	314	344	32.6	292	3.42	970.74	436.15	123%	9.827	54.29	3.712	0
208	208/1	3.87	246	279	344	32.6	292	3.42	885.18	442.35	100%	9.815	29.43	4.032	1
208	208/2	4	209	240	344			3.42	860.91	470.27	83%	13.251	77.85	4.167	0
209	209	3.7	275	321	341	33.7	269	3.72	1037.90	501.27	107%	9.429	41.26	3.500	1
211	211	3.9	256	284	302	33.3	257	3.89	1044.08	527.50	98%	10.853	35.84	4.171	0
212	212	4.18	213	252	302	33.3	257	3.89	989.70	533.59	86%	11.743	51.44	4.074	0
213	213	4.18	177	213	302	33.3	257	3.89	983.60	597.37	66%	11.769	37.48	4.992	1
214	214/1	3.7	287	305	331	33.5	264	3.79	1033.35	487.29	112%	13.053	79.61	4.128	1
215	215	3.87	246	286	331	33.5	264	3.79	1010.26	499.48	102%	12.341	59.43	4.638	1
216	216	3.97	213	237	331	33.5	264	3.79	980.44	559.78	75%	12.450	63.02	4.941	0
217	217/1	3.85	292	320	360	31.8	266	3.76	1120.42	536.83	109%	14.471	50.58	4.635	1
217	217/2	4.17	250	295	360			3.76	962.10	498.32	93%	14.539	67.77	3.788	1
217	217/3	3.95	199	254	360			3.76	1007.25	547.18	84%	15.715	82.05	5.598	1
218	218	3.85	267	308	355	28.8	253	3.95	1015.43	477.46	113%	11.958	50.55	4.683	1
219	219	3.77	186	226	355	28.8	253	3.95	993.36	557.37	78%	11.566	61.58	6.693	0
220	220/1	3.77	275	317	337	31.3	254	3.94	1063.18	479.30	122%	10.847	52.15	2.990	0
220	220/2	3.95	247	274	337			3.94	961.68	462.33	108%	12.871	66.30	3.953	1
220	220/4	3.95	165	209	337			3.94	922.72	494.75	86%	13.162	38.56	5.762	1
221	221	4.08	249	280	312	31.2	253	3.95	1035.32	532.07	95%	12.106	58.40	4.964	0
223	223	3.57	293	337	355	29.8	264	3.79	1024.52	489.56	109%	11.297	50.34	3.338	1
224	224/1	3.95	249	291	355	29.8	264	3.79	905.92	454.37	100%	13.458	64.69	3.580	1
224	224/2	4.1	209	245	355			3.79	848.61	490.23	73%	12.743	71.78	3.931	1
226	226	3.92	187	222	278	28.9	259	3.86	993.64	507.95	96%	11.902	74.61	5.533	0
227	227	3.82	197	215	237	27.9	247	4.05	1063.77	492.56	116%	9.269	34.02	4.213	0
229	229	4.05	236	263	334	29.2	270	3.70	964.92	503.28	92%	10.320	53.76	4.703	0
230	230/1	4.1	196	234	334	29.2	270	3.70	946.70	520.63	82%	12.428	47.09	4.992	1
230	230/2	3.95	150	191	334			3.70	892.03	530.60	68%	14.412	52.23	5.784	1
228	228	4.13	160	194	237	27.9	247	4.05				11.636	39.42	4.821	0

Data for sites 3,4 and 5 on following page.

		Log Data			Tree Data									Hardness	
Tree No.	**Log No.**	Hitman km/s	SED	LED	DBH	Height	Fakopp	Fakopp km/s	Green Density	Basic density	MC Average	MOE (GPA)	MOR (MPA)	Tangential KN	Visual Grading (1=in grade)
301	301	3.49	192	255	253	19	284	3.52	968.12	441.80	119%	9.749	50.42	3.106	1
302	302	3.39	188	257	275	18	286	3.50	979.42	476.07	106%	9.121	47.63	4.155	1
303	303	3.7	160	216	223	18.3	279	3.58	946.04	454.83	108%	10.262	64.10	3.579	1
304	304	3.72	144	203	261	19.1	299	3.34	919.18	485.15	89%	11.387	69.16	4.978	1
305	305	3.34	135	198	228	16.3	307	3.26	814.28	481.30	69%	8.992	36.49	3.716	1
306	306	3.95	149	190	220	18.2	262	3.82	941.18	466.73	102%	12.627	67.46	4.312	1
307	307	3.7	162	216	219	18.2	267	3.75	984.90	525.28	88%	9.968	79.07	4.412	1
308	308	3.65	164	210	221	18.2	277	3.61	963.97	448.72	115%	11.200	49.11	4.837	1
309	309	3.7	139	196	214	18	268	3.73	924.23	485.52	90%	9.900	55.97	6.564	1
310	310	3.59	189	264	265	19.2	282	3.55	1003.45	527.46	90%	8.979	33.58	4.641	1
311	311	3.97	166	198	213	18	259	3.86	977.70	520.20	88%	11.520	53.25	4.885	0
312	312	3.59	176	205	245	18.8	281	3.56	916.93	443.40	107%	9.086	53.54	3.945	1
313	313	3.75	166	223	227	20.3	265	3.77	921.54	504.33	83%	8.840	53.48	4.836	0
314	314	3.65	183	237	242	18.7	269	3.72	1018.33	499.79	104%	11.333	77.07	4.713	1
315	315	3.28	176	223	239	18.7	279	3.58	963.70	518.82	86%	11.439	63.06	6.531	1
316	316	3.75	185	234	255	19	281	3.56	937.70	504.94	86%	9.608	30.90	4.966	1
317	317	3.57	174	230	243	18.7	299	3.34	944.54	453.27	108%	9.329	44.73	6.379	0
319	319	3.67	160	205	218	18.1	281	3.56	949.19	466.36	104%	11.484	68.69	4.219	1
320	320	3.8	246	295	333	20.3	273	3.66	894.14	518.59	73%	11.354	59.02	5.661	1
321	321	3.24	197	248	268	19.3	294	3.40	942.43	455.55	107%	9.251	56.60	3.999	1
323	323	3.7	155	200	213	18	283	3.53	958.51	505.05	90%	11.351	46.36	5.191	1
324	324	3.57	154	221	240	18.7	286	3.50	965.10	507.55	90%	8.954	28.65	4.309	1
326	326	3.62	174	238	261	19.1	288	3.47	929.64	460.07	102%	10.216	60.12	4.279	1
327	327	3.49	203	261	287	19.6	287	3.48	956.45	455.91	110%	10.675	66.62	4.192	1
328	328	3.8	165	210	216	18.1	271	3.69	945.80	465.46	103%	11.306	60.29	3.774	1
329	329	3.59	155	200	220	18.2	287	3.48	984.60	474.59	107%	10.311	59.87	4.476	1
330	330	3.47	174	227	244	18.8	286	3.50	976.40	491.93	98%	10.181	67.49	5.174	1
331	331	3.44	207	265	273	19.4	289	3.46	992.43	473.82	110%	8.780	52.05	4.509	1
322	322	3.72	177	226	243	18.7	281	3.56	938.03	473.35	98%	9.681	51.43		0
401	401	3.29	166	245	236	19.7	311	3.22	786.22	432.85	82%	9.185	32.62	3.158	1
402	402	3.27	173	222	227	18.7	302	3.31	940.37	457.75	105%	10.256	52.25	5.141	0
403	403	3.49	170	225	235	19.7	284	3.52	834.00	444.69	88%	8.684	42.66	4.694	1
404	404	3.44	166	211	220	19.4	301	3.32	738.44	450.13	64%	8.805	38.88	4.433	1
405	405/1	3.59	218	270	276	22.6	282	3.55	850.21	433.16	96%	8.250	15.61	2.819	0
405	405/2	3.85	166	217	276			3.55	816.49	458.53	78%	9.787	57.50	3.628	1
407	407	3.52	160	195	207	19.1	287	3.48	856.97	453.47	89%	10.893	68.77	4.458	1
408	408	3.19	185	238	244	19.8	272	3.68	828.99	423.12	97%	4.450	19.54	3.897	1
409	409	3.65	158	196	213	19.2	274	3.65	897.25	476.57	88%	9.160	38.08	4.848	0
410	410	3.27	150	205	215	19.5	304	3.29	840.52	433.54	94%	7.867	19.92	4.744	1
411	411	3.65	152	196	208	19.1	279	3.58	777.40	459.12	69%	10.067	36.71	6.371	0
412	412	3.27	193	250	260	20.1	313	3.19	876.90	487.52	80%	8.291	36.84	4.553	0
413	413	3.47	204	255	262	19.2	283	3.53	944.19	469.36	101%	9.534	31.57	3.735	1
414	414	3.39	185	255	241	19.8	280	3.57	807.97	480.24	68%	6.597	30.21	4.330	0
416	416	3.57	141	203	216	19.3	276	3.62	910.95	519.56	75%	8.176	20.63	2.664	0
418	418	3.21	180	240	297	20.6	300	3.33	893.33	457.44	95%	6.344	30.50	3.594	1
419	419	3.06	174	228	273	20.3	328	3.05	904.52	454.66	99%	8.447	55.53	6.952	1
420	420	3.65	168	200	212	19.2	285	3.51	782.70	439.24	78%	9.367	57.17	4.731	1
421	421/1	3.54	176	218	220	19.4	289	3.46	930.00	506.25	84%	7.866	29.58	4.576	1
422	422	3.47	170	200	214	19.2	300	3.33	888.90	418.05	113%	8.626	39.55	3.643	1
423	423	3.67	177	220	226	19.5	276	3.62	798.46	445.63	79%	9.657	54.49	4.020	1
424	424	3.75	144	180	216	19.3	276	3.62	755.39	481.72	57%	7.649	16.30	4.558	1
425	425	3.62	169	205	219	19.3	271	3.69	856.61	480.60	78%	10.856	59.33	4.323	1
427	427	3.16	203	266	273	20.3	308	3.25	830.46	430.58	93%	7.091	46.04	3.175	1
428	428	3.27	186	250	265	20.1	329	3.04	908.15	433.01	110%	7.581	37.73	5.415	1
430	430	3.32	198	265	274	20.3	287	3.48	921.07	436.77	111%	7.613	42.82	3.087	1
415	415	3.57	158	210	222	19.2	294	3.40				9.176	42.29	4.910	0
406	406/1	3.62	188	232	237	21.4	278	3.60				9.523	34.39	4.619	1
406	406/2	3.87	148	182	237			3.60				11.347	47.20	4.941	1
501	501	3.27	175	212	257	19.1	314	3.18	1053.43	455.31	131%	8.215	45.79	3.981	1
502	502	3.24	204	253	272	19.9	298	3.36	969.18	422.91	129%	9.864	63.77	3.678	1
503	503	3.34	166	225	295	20.5	300	3.33	947.07	491.72	93%	10.937	63.42	4.933	1
504	504	3.32	199	240	244	19.8	276	3.62	1093.35	495.95	120%	9.174	29.58	3.726	1
505	505	2.99	221	282	296	19.5	308	3.25	1040.88	443.58	135%	6.758	36.19	3.580	0
506	506	3.11	176	221	241	19	310	3.23	1065.96	468.22	128%	9.802	30.74	3.444	1
507	507/1	3.04	215	271	267	19.1	299	3.34	1045.09	437.00	139%	9.106	58.45	5.516	1
507	507/2	3.27	141	202	267			3.34	1113.83	487.37	129%	10.032	60.97	4.687	0
508	508	3.01	163	220	229	18.5	338	2.96	994.46	462.92	115%	8.827	45.62	3.552	1
509	509	3.37	182	222	231	19.7	281	3.56	1010.43	412.35	145%	12.224	73.82	3.458	1
510	510	3.29	234	287	296	20.6	288	3.47	1049.47	454.71	131%	9.535	70.71	3.968	1
511	511	3.27	172	221	260	19.6	288	3.47	1125.19	489.15	130%	12.380	72.24	4.498	1
512	512	3.09	177	223	239	18.9	310	3.23	1083.18	442.22	145%	9.203	66.44	3.195	1
514	514	3.16	197	255	257	18.6	308	3.25	1015.00	490.55	107%	10.400	64.86	3.073	1
516	516	3.09	196	252	262	19.6	320	3.13	1039.69	434.65	139%	7.632	42.42	3.320	1
517	517	3.29	177	228	222	18.3	300	3.33	1054.65	489.99	115%	8.782	61.21	3.087	1
518	518	3.32	200	250	248	19.2	288	3.47	1077.24	480.44	124%	10.158	47.24	3.161	1
519	519	3.42	188	227	237	18.8	272	3.68	1012.16	522.22	94%	9.734	26.86	4.668	1
520	520	3.16	192	234	237	19.6	286	3.50	1062.70	429.18	148%	10.196	58.95	3.507	1
521	521	3.21	189	223	253	19.4	289	3.46	1011.08	425.48	138%	10.347	40.06	3.100	1
522	522	3.21	182	224	267	19.8	281	3.56	1064.26	442.70	141%	8.817	26.89	3.404	1
523	523	3.34	222	276	292	20.5	284	3.52	1056.32	473.29	123%	11.314	66.88	4.812	1
524	524/1	3.09	166	201	213	17.9	301	3.32	1063.95	405.77	162%	7.481	39.97	3.230	1
525	525	3.14	207	263	273	20.4	307	3.26	1081.57	503.32	115%	9.581	52.39	3.975	1
526	526	3.01	229	295	291	20.4	301	3.32	1063.84	477.43	123%	8.884	50.12	2.841	1
527	527	3.44	185	226	232	18.7	269	3.72	1012.40	465.58	118%	9.675	43.17	3.843	1
528	528	3.44	190	244	261	20.9	281	3.56	1026.87	426.23	141%	9.434	46.72	3.128	1
529	529	3.06	188	229	232	18.7	295	3.39	1065.26	458.66	132%	6.886	37.42	3.534	1
530	530	3.29	176	223	230	18.8	274	3.65	980.77	439.59	123%	8.330	61.52	3.404	1
513	513	3.32	210	251	263	21.1	280	3.57				8.604	56.35	2.943	1

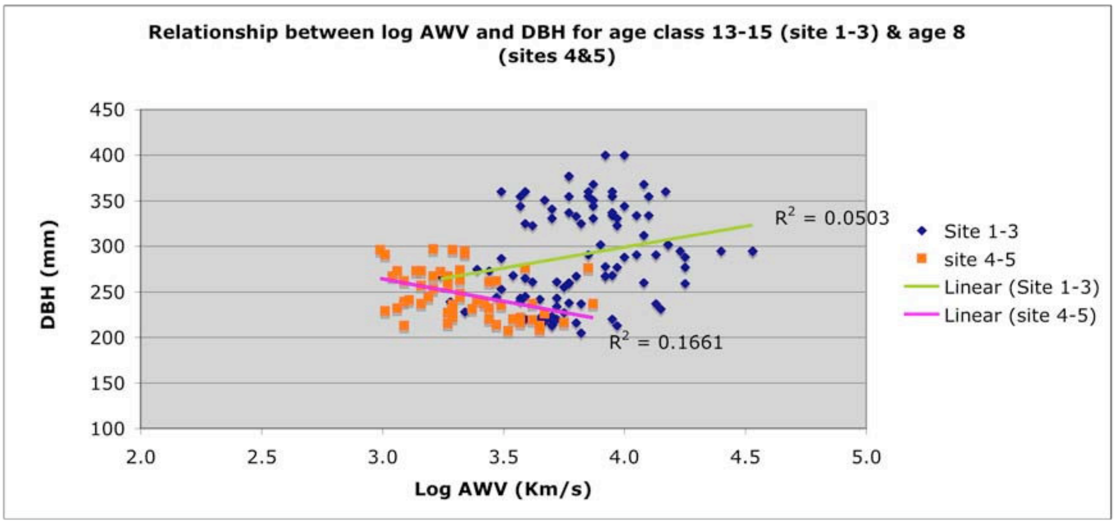
Blank cells identify missing data - excluded from analysis.

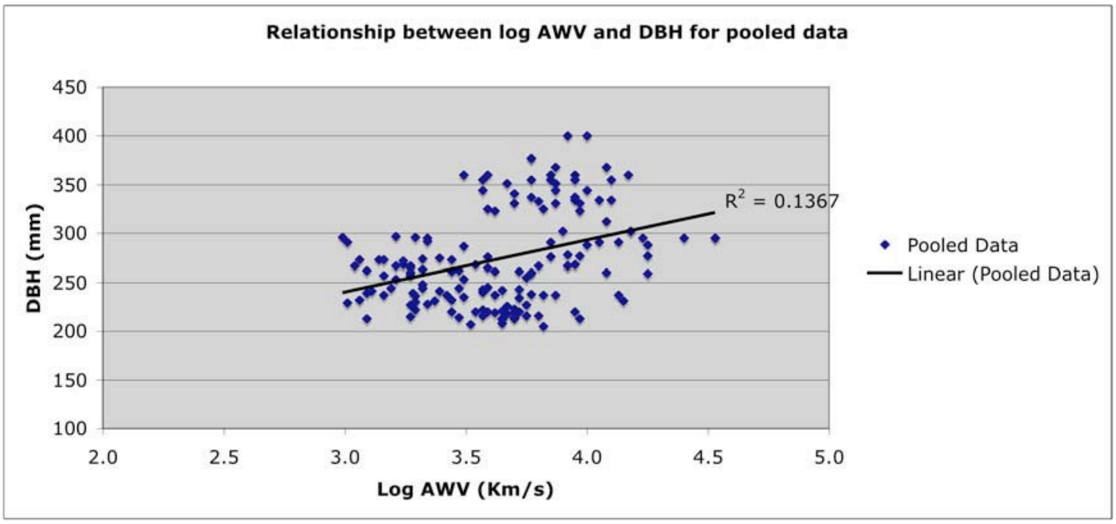
8.4 Details of analysis using age and age+site as fixed effects (excluding upper logs).

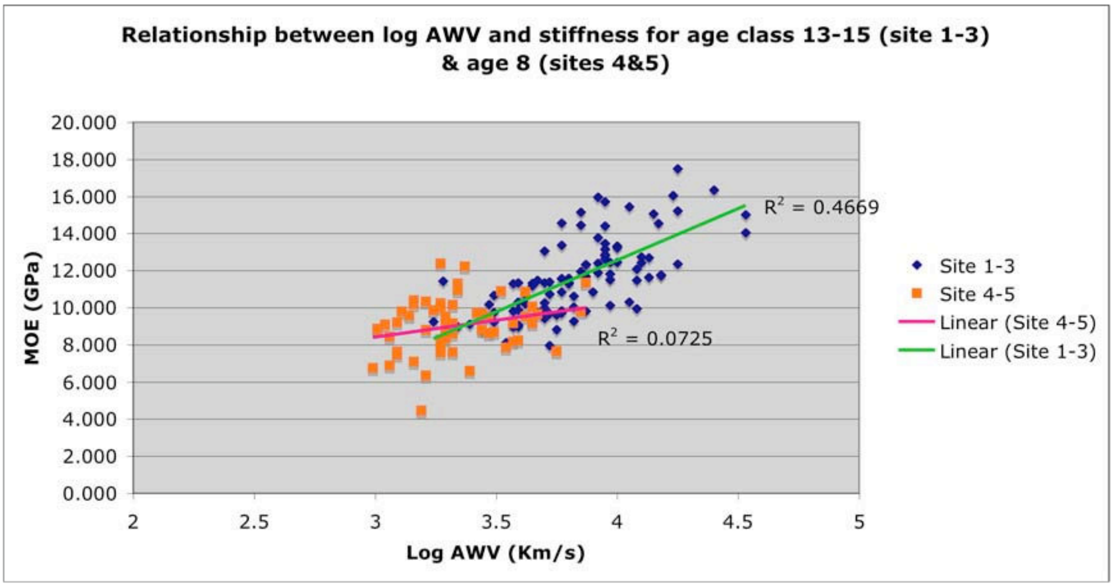
Age (years)	fakopp	hitman	basic density	moisture content	MOE	MOR	Janka hardness
8	3.421	3.327	457.50	1.090	8.970	44.82	4.00
13	3.688	3.798	489.50	0.978	11.320	53.85	4.34
significance of difference	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p=0.026

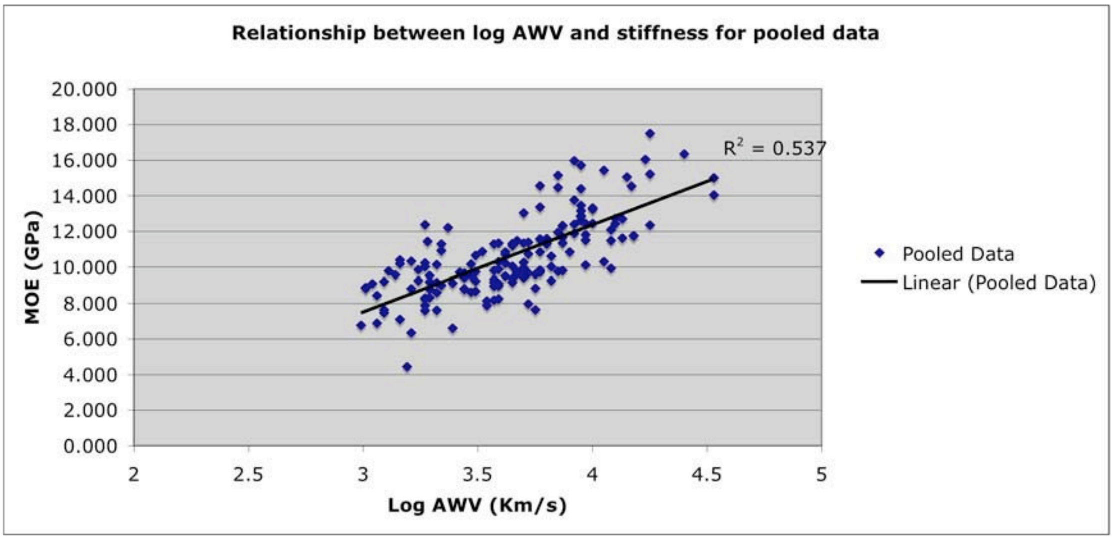
Analysis of age + age.site	fakopp	hitman	basic density	moisture content	MOE	MOR	Janka hardness
significance of difference:							
age	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p<0.001	p=0.019
age.site	p<0.001	p<0.001	p=0.003	p<0.001	p<0.001	p=0.005	p<0.001

8.5 Illustration of correlations analysed by age class and as a pooled data set.






Relationship between log AWV and stiffness for age class 13-15 (site 1-3) & age 8 (sites 4&5)
MOE (GPa)
Log AWV (Km/s)
R^2 = 0.4669
R^2 = 0.0725
Site 1-3
Site 4-5
Linear (Site 4-5)
Linear (Site 1-3)


Relationship between log AWV and stiffness for pooled data
MOE (GPa)
Log AWV (Km/s)
R^2 = 0.537
Pooled Data
Linear (Pooled Data)

9 Acknowledgments

The authors gratefully acknowledge the contribution of staff at Forest Enterprises Australia Ltd (FEA) for their considerable support in this project.

They also thank Dr Chris Harwood of CRC for forestry for valuable comments on the project report.

For assistance during the field work and lab testing component of the project we would like to thank Dr David Wood of the University of Tasmania's School of Engineering, as well as Steve Wright, Samuel Gadient and Steven Hindrum from the Centre for Sustainable Architecture with Wood.