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NON-DESTRUCTIVE ULTRASONIC TESTING METHOD FOR DETERMINING BENDING STRENGTH PROPERTIES OF GMELINA WOOD (*GMELINA ARBOREA*)

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KARLINASARI, L., WAHYUNA, M. E. & NUGROHO, N. 2008. Non-destructive ultrasonic testing method for determining bending strength properties of gmelina wood (*Gmelina arborea*). The objective of this study was to investigate the usefulness of non-destructive ultrasonic testing method in evaluating wood strength and stiffness of gmelina (*Gmelina arborea*) from several positions in the tree, both vertically and horizontally. These tests were conducted on 72 small clear wood specimens of dimensions 5 × 5 × 76 cm. The effects of position of specimen in a tree could be identified with ultrasonic wave velocity (Vus). The dynamic testing determined by ultrasonic method, Vus and dynamic modulus of elasticity (MOEd), were highly correlated with the static bending test (static modulus of elasticity and modulus of rupture). The developed regression models were significant. Ultrasonic method seems applicable in situations where static bending test is not feasible.

Keywords: ultrasonic, wave velocity, MOEd, MOEs, MOR

KARLINASARI, L., WAHYUNA, M. E. & NUGROHO, N. 2008. Kaedah ujian ultrasonik tak memusnah untuk menentukan ciri-ciri kekuatan lentur kayu gmelina (*Gmelina arborea*). Kajian ini menyelidik keberkesanan kaedah ujian ultrasonik tak memusnah dalam menilai kekuatan kayu dan ketegaran kayu gmelina (*Gmelina arborea*) pada beberapa kedudukan dalam pokok iaitu secara menegak dan mendatar. Ujian dijalankan terhadap 72 sampel kayu kecil berukuran 5 cm × 5 cm × 76 cm. Kesan kedudukan spesimen dalam pokok boleh dikesan dengan halaju gelombang ultrasonik (Vus). Ujian dinamik Vus dan modulus kekenyalan dinamik (MOEd) menggunakan kaedah ultrasonik mempunyai korelasi yang tinggi dengan ujian lentur statik (modulus kekenyalan statik dan modulus kepecahan). Model regresi yang dibangunkan adalah signifikan. Kajian ultrasonik dapat digunakan dalam keadaan apabila ujian lentur statik tidak boleh dilaksanakan.

INTRODUCTION

In mechanical property testing, there are two kinds of testing: destructive and non-destructive. Non-destructive testing is defined as the science of identifying the physical and mechanical properties of an element of a given material without altering its final application capacity (Ross *et al.* 1998). Non-destructive evaluation method has been extensively developed for sorting or grading wood products. One of these evaluations is ultrasonic wave propagation method, which has been investigated on tree, round wood, logs, board, glulam and in-situ structural building condition (Sandoz & Wei 2006). There are three characteristics used to evaluate wood strength quality: modulus of rupture (wood strength), modulus of elasticity (stiffness) and density. Determination of bending properties of wood by non-destructive ultrasonic wave propagation method is based on the parameter of speed (velocity) of sound, modulus of elasticity and density. There is a correlation between MOE and MOR developed to evaluate strength properties of wood. Some researchers worked with non-destructive ultrasonic testing. Oliveira *et al.* (2002) reported correlation coefficient of about 0.6 for cupiuba and jatoba beams (Brazilian wood) for the relationship between dynamic MOE (MOEd) and the static bending test (MOEs and MOR). Studies conducted by Karlinasari *et al.* (2005) revealed that the correlation coefficient ranged from 0.3–0.9 for the relationship between MOEd, MOEs and MOR for data from small clear specimen of some tropical woods (sengon,

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meranti, manii, mangium, agathis and pine) in small sample size. Most of the developed regression models were statistically significant at the 0.05 confidence level.

Although application efforts have paved the way for the successful use of non-destructive evaluation, in Indonesia, research and application of such evaluation of wood are still limited. However, non-destructive method could be a promising alternative to evaluate wood quality in an effective, efficient and objective way.

Gmelina (*Gmelina arborea*) is a fast-growing species and planted in plantation forest. Gmelina wood can be used as light construction wood, handicraft materials, furniture, fancy veneer, match materials, and pulp and paper. It has good working properties (sawing, moulding, peeling, turning and sanding) and physical–mechanical properties (Djodjosoebroto 2003). The density is 420–610 kg m^{-3}; the average MOE and MOR values are 9.59 GPa and 57.8 MPa respectively (Mahbub 2000).

The objective of this study was to investigate the usefulness of non-destructive ultrasonic method for evaluating wood strength and stiffness of gmelina from several positions in the tree, both vertically and horizontally.

MATERIALS AND METHODS

Three trees of *G. arborea* of about six years old (diameter about 30 cm) were selected randomly from the field site of the Faculty of Forestry, Bogor Agricultural University in Campus Darmaga Bogor. Three bole sections of 200 cm length were cut from felled trees. They were defined as vertical position sample: bottom, middle and top (Figure 1). A section produced eight specimens in horizontal position representing heartwood and sapwood (Figure 2) with a dimension of 5 × 5 cm in cross-section and length of 76 cm in accordance with ASTM D 143 (ASTM 2002). Heartwood is defined as a cylinder of wood in the centre of a tree which acts as a no functional conductive or storage cell and is darker in colour. There were a total of 72 specimens. All specimens were prepared in air-dried condition (average MC values was 16%).

Non-destructive and static bending tests were applied to the specimens. Non-destructive test was carried out to measure ultrasonic wave velocity using SylvatestDuo device (f=22 kHz) (Figure 3). The transmitting transducer and receiving transducer of the device were inserted into the wood on each end. The distance between the two transducers (d) was measured and the time of flight of ultrasonic waves (t) was recorded from three repeated readings. The ultrasonic velocity (Vus) was measured using the following formula:

$$\text{Vus} = \frac{d}{t}\, 10^{6}\ (\text{m s}^{-1})$$

The dynamic modulus of elasticity was expressed by the following equations (Carter *et al.* 2005).

$$\text{MOEd} = \rho V^{2}$$

where MOEd is the dynamic modulus of elasticity (MPa), ρ is the mass density (kg m^{-3}) and Vus is ultrasonic wave velocity (m s^{-1}).

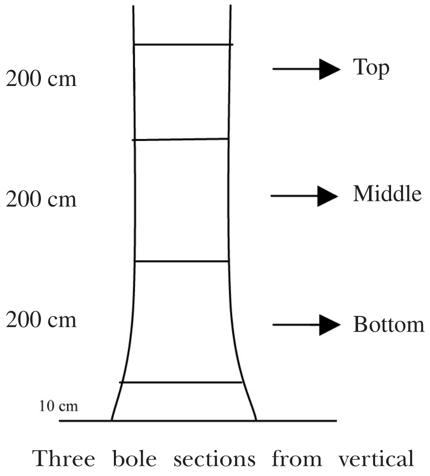

Figure 1 Three bole sections from vertical position sample

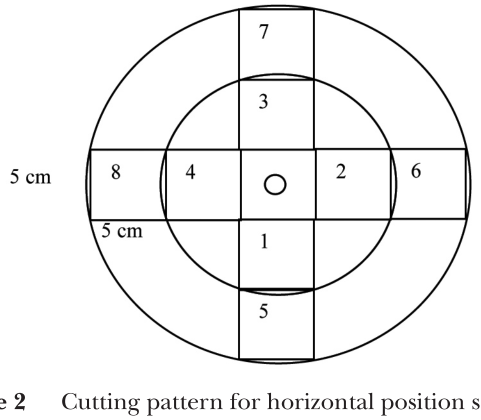

Figure 2 Cutting pattern for horizontal position sample (1, 2, 3, 4 represent heartwood and 5, 6, 7, 8 represent sapwood)

Figure 3 Non-destructive ultrasonic device SylvatestDuo

Static bending test was carried out to determine the static modulus of elasticity (MOEs) and the modulus of rupture (MOR) using a Baldwin Universal Testing Machine. One point loading was done in that static test. Following each static bending test, 2 × 2 × 2 cm sample was cut near the failure part from each specimen for measuring density and moisture content. The density was calculated from the mass and volume of the beam and the moisture content was measured by the drying and weighing method (Tsoumis 1991).

Statistical analysis was performed to determine the influence of sample position in the tree, and the relationship between dynamic ultrasonic test and static bending test using Statistical Product and Service Solution (SPSS) 13.0 for window.

RESULTS AND DISCUSSION

Physical characteristics

The average density of gmelina wood was 550 kg m^{-3} for heartwood and 540 kg m^{-3} for sapwood (Table 1). The average densities for the bottom, middle and top sections were 540, 530 and 560 kg m^{-3} respectively. The density values were categorized as middle wood density with coefficient variation below 10%. The findings were in accordance with those made by other researchers (Mahbub 2000, Djodjosoebroto 2003), that the density of gmelina wood ranged from 350–610 kg m^{-3}. The highest wood density was in the top section, followed by the bottom and middle sections. Analysis of variance (Table 2) indicated differences with respect to the vertical position but no difference with respect to the horizontal position. In the horizontal position, the highest wood density was in the heartwood, followed by the sapwood. This is in accordance with the general rule that at any given height in the trunk there is usually a general increase in density outwards from the pith (Desch & Dinwoodie 1981, Anonymous 1999).

The Vus average value of heartwood was 4243 m s^{-1} (Table 1). It was about 5% greater than that of sapwood (4036 m s^{-1}). In the vertical position, the Vus measured for the bottom, middle and top sections were 4030, 4223 and 4166 m s^{-1} respectively. Analysis of variance indicated no significant difference in Vus in the vertical position (Table 2). However, significant difference was found in the horizontal position. *t*-test showed no significant difference in Vus between heartwood and sapwood (Table 3). Vus did not seem to follow the same pattern as density. Perhaps, Vus was sensitive on microstructural characteristic as a medium of ultrasonic wave propagation. Previous study had shown that Vus was relatively high in the middle part of the height of a tree, followed by top and bottom for Douglas fir in both control and pruned trees (Bucur 2006).

Dynamic and static bending tests

Dynamic MOE average value for heartwood was 10.17 GPa and sapwood, 9.02 GPa (Table 1). Dynamic MOE in the top position was highest (9.97 GPa), followed by middle (9.78 GPa) and bottom positions (9.03 GPa) (Table 1). Static bending test indicated that the MOEs averages

Table 1 Physical characteristics and bending strength properties of gmelina

Position	Value	ρ (kg m^{-3})	MC (%)	Vus (m s^{-1})	MOEd (GPa)	MOEs (GPa)	MOR (MPa)
				Heartwood			
Bottom	Average	550	16.45	4226	10.00	9.07	48.74
	CV (%)	6.03	4.87	8.39	19.40	16.50	14.83
Middle	Average	540	16.63	4299	10.32	9.37	49.42
	CV (%)	9.66	7.22	8.28	22.50	21.62	14.14
Top	Average	570	16.96	4204	10.19	9.57	50.59
	CV (%)	4.88	5.74	6.11	11.80	12.63	12.28
Average heartwood		550	16.68	4243	10.17	9.34	49.58
CV (%)		7.13	5.99	7.52	18.00	16.92	13.45
				Sapwood			
Bottom	Average	530	16.21	3833	8.06	7.27	41.05
	CV (%)	7.37	5.38	10.90	25.48	25.78	15.09
Middle	Average	530	16.22	4148	9.25	8.33	45.48
	CV (%)	9.89	5.41	9.50	19.59	18.65	15.13
Top	Average	560	17.00	4127	9.75	8.67	47.05
	CV (%)	8.42	6.71	6.87	16.17	17.79	17.18
Average sapwood		540	16.48	4036	9.02	8.09	44.53
CV (%)		8.83	6.16	9.60	21.19	21.32	16.51
Average bottom		540	16.33	4030	9.03	8.17	44.90
CV (%)		6.70	5.07	10.70	24.27	23.20	17.06
Average middle		530	16.42	4223	9.78	8.85	47.45
CV (%)		9.77	6.39	8.90	21.57	20.83	14.90
Average top		560	16.98	4166	9.97	9.12	48.88
CV (%)		5.95	6.10	6.42	13.93	15.68	14.90

ρ = density; MC = moisture content; CV=coefficient of variation; Vus = ultrasonic velocity; MOEd = dynamic modulus of elasticity; MOEs = static modulus of elasticity; MOR = modulus of rupture

Table 2 Summary of analysis of variance (ANOVA) of the influence of position sample in tree as a factor on density, Vus, MOEd, MOEs and MOR values of gmelina in the horizontal and vertical positions

Source	Density	Vus	MOEd	MOEs	MOR
	p value	p value	p-value	p value	p value
Horizontal position	0.208 ns	0.014*	0.011*	0.002*	0.003*
Vertical position	0.043*	0.151 ns	0.187 ns	0.124 ns	0.148 ns
Horizontal × vertical	0.828 ns	0.265 ns	0.376 ns	0.597 ns	0.527 ns

p value = probability at the 0.05 confidence level, * = significant at the 0.05 confidence level, ns = not significant at the 0.05 confidence level

Table 3 Summary of statistical comparison *t*-test for equality of means analyses between heartwood and sapwood on density, Vus, MOEd, MOEs and MOR values of gmelina in the horizontal and vertical positions

	Density	Vus	MOEd	MOEs	MOR
	Sig. (2-tailed)	Sig. (2-tailed)	Sig. (2-tailed)	Sig. (2-tailed)	Sig. (2-tailed)
Equal variances assumed	0.820*	0.016 ns	0.010 ns	0.002 ns	0.003 ns
Equal variances not assumed	0.821 ns	0.016 ns	0.010 ns	0.002 ns	0.003 ns

* = Significant at the 0.05 confidence level, ns = not significant at the 0.05 confidence level

were 9.12, 8.85 and 8.17 GPa for the top, middle and bottom positions respectively. The MOEs average values were 9.34 GPa for heartwood and 8.09 GPa for sapwood. In the vertical position, the MOR were 48.9, 47.5 and 44.9 MPa for the top, middle and bottom positions respectively. The MOR average values were 49.6 MPa for heartwood and 44.5 MPa for sapwood. Analysis of variance indicated no significant difference in both dynamic and static bending test means on vertical position. However, significant difference was found in the horizontal position (Table 2). *t*-test showed no significant difference in MOEd, MOEs and MOR means between heartwood and sapwood (Table 3). The results are in line with those of Desch and Dinwoodie (1981) who reported that the mechanical strength properties of sapwood are a little lower than heartwood, but the differences are not significant.

The MOEd values were 9–11% higher than those of MOEs. The accuracy of the determination of MOE of wood by the dynamic test was higher than that of the static test. The difference is possibly due to the viscoelastic nature of wood. Concerning wood vibration characteristic, the restored elastic force is proportional to the velocity. When force is applied to wood for a short time, the wood responds as a solid elastic behaviour. With longer application of force, the materials show as viscous liquid behavior. This behaviour proves that in an ultrasonic test, the modulus of elasticity is greater than the static bending test (long duration) (Oliveira *et al.* 2002). According to Bodig and Jayne (1993), and Tsoumis (1991), MOE obtained by vibration test was 5–15% higher than those obtained by a static test. Bucur (2006) reported that the value of MOE determined from the dynamic test was about 5–10% higher than that from the static test. Oliveira *et al.* (2002) obtained values for dynamic MOE 17–20% higher than those of static test for Brazilians wood beams using ultrasonic method. Research by Karlinasari (2005, 2007) showed that the dynamic ultrasonic test was more than 50% higher than static test on small specimen using BS 373 (Anonymous 1957) standard and secondary method specimen in ASTM D 143.

Dynamic and static bending relationships

There were strong correlations between Vus and static bending test (MOEs and MOR). The correlation coefficients were found to be 0.87 for MOEs and 0.85 for MOR (Table 4). The developed regression models were statistically significant. The relationship between MOEd of wood and MOEs and MOR were well correlated: r = 0.96 and r = 0.88 respectively. MOEs and MOR was also well correlated (r = 0.92). The linear regression analyses for these relationships indicated that the developed regression models were statistically significant at the 0.05 confidence level. It is highly promising that the non-destructive ultrasonic testing method can be used to evaluate bending strength properties in situations where a static bending test is not feasible to undertake.

CONCLUSIONS

This study showed that the bending strength of gmelina wood could be determined by destructive and non-destructive ultrasonic testing methods. The effect of position of specimen in a tree can be identified with ultrasonic wave velocity. Dynamic MOE (MOEd) followed

Table 4 Regression model for relationship between dynamic ultrasonic test (Vus, MOEd) and static bending test (MOEs and MOR) of gmelina

Regression model	Correlation coefficient r	Coefficient of determination r^2	Significance of model
MOEs = 0.0042 Vus – 8.6482	0.87	0.77	0.00*
MOR = 0.0171 Vus – 23.784	0.85	0.72	0.00*
MOEs = 0.8687 MOEd + 0.3836	0.96	0.92	0.00*
MOR = 3.3766 MOEd + 14.657	0.88	0.78	0.00*
MOR = 3.8755 MOEs + 13.267	0.92	0.84	0.00*

* = significant at the 0.05 confidence level

similar trend as the MOEs and MOR. There was good correlation between ultrasonic velocity (Vus) and static bending test values (MOE and MOR). A slightly better result was obtained for correlation between dynamic MOE with both MOEs and MOR. All developed regression models were statistically significant at the 0.05 confidence level. Although the static bending test (MOEs) is generally recognized as a more desirable method of determining strength properties (MOR), these results have indicated that ultrasonic method (Vus and MOEd) may also be useful as a non-destructive method for predicting the MOR of gmelina wood.

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