VARIATIONS OF MECHANICAL PROPERTIES IN PLANTATION TIMBERS OF JELUTONG (*DYERA COSTULATA*) AND KHAYA (*KHAYA IVORENSIS*) ALONG THE RADIAL AND VERTICAL POSITIONS

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Thoroughgoing efforts are regularly being carried out for the development and promotion of plantation timbers. Continuous acquisition of physical and mechanical data will ensure the utmost utilisation of these timbers. Knowledge in variation of mechanical properties of plantation timbers at different positions in a tree is important for the successful use of the timber as a solid material. The present study used young plantation trees to obtain basic information on the appropriate uses of thinning materials (i.e. trees cut down during thinning). Jelutong (*Dyera costulata*) and khaya (*Khaya ivorensis*) aged 10 and 15 years old respectively were selected as samples. Mechanical analyses were conducted based on radial positions from pith to bark and vertical positions of bottom, middle and top logs. Evaluations were made based on the modulus of rupture, modulus of elasticity, compressive strength parallel to the grain, shear strength parallel to the grain, tensile strength parallel to the grain, Janka hardness and specific gravity. Mechanical properties of jelutong and khaya along the radial and vertical positions were not symmetry. Nevertheless, some noticeable patterns of the mechanical properties relative to the radial and vertical positions were observed.

Keywords: Plantation forestry, wood strength, basic density

INTRODUCTION

In Malaysia, studies of mechanical properties of plantation timbers have been carried out since the establishment of the national plantation forestry programmes. For optimum utilisation of plantation outputs (e.g. thinning material, juvenile trees and mature trees) information on physical and mechanical characteristics of the timber materials are greatly required.

Variations in mechanical properties of *Macaranga gigantifolia* and *M. hypoleuca* have been reported by Trockenbrodt et al. (2000). Eight trees per species were tested with diameters at breast height of 280 to 390 mm. For both species, the mechanical properties showed increasing values from the pith to bark. The modulus of rupture (MOR) values were 37 N mm^{-1} (inner position), 41 N mm^{-1} (middle position) and 49 N mm^{-1} (outer position). Similar patterns were observed for modulus of elasticity (MOE), compressive strength, shear strength, hardness and density of the timber.

Mechanical properties of timber are directly related to specific gravity. A study of 5-year-old *Acacia mangium* showed an increase in specific gravity from the pith to the region near the bark (Ani & Lim 1993). The authors also observed some significant variations in the specific gravity along the longitudinal direction but with no particular trend. However, the specific gravity of samples from 14-year-old *A. mangium* showed a different pattern (Lim & Gan 2000b). Radial variation increased from pith to the intermediated region before decreasing towards the bark.

Specific gravity values for 16- and 20-year-old *Acacia mangium* increased from pith to bark (Lim & Gan 2011). Variation in specific gravity in the longitudinal direction was less consistent. However, the bottom end of both trees showed the highest specific gravities. Variation in specific gravity along radial direction of 8-year-old *Azadirachta excelsa* showed no specific pattern (Lim & Gan 2000a). However, from the pith to the bark, considerable gradual increase in the number of vessels mm^{-2} was observed until 30% height, whereas the trend was reversed at 50% height to the top. No specific patterns were observed in the variations of fibre length, diameter and wall thickness.

Ten-year-old *Tectona grandis* of two planting densities showed an increase in specific gravity of the timber from pith to bark, varying from 0.38 to 0.69 (Moya et al. 2003). In the higher planting density, specific gravity increased rapidly from the pith and reached a plateau near the bark. In the lower planting density, a slight decrease in specific gravity was observed near the bark. This suggested that plantation spacing affected specific gravity of the timber at the time of growth.

Variation statistics of mechanical properties within a log is important for effective use of plantation timbers. Engineers and designers require explicit data on the uniformity of mechanical properties within a tree to estimate its lowest strength. During processing of logs into sawn timber, knowledge in variation of properties could directly affect sawing and drying procedures. Information on variation of mechanical properties could also assist in the development of yield rotation scheme. This study was based on the hypothesis that the physical and mechanical characteristics of timber vary within a tree.

MATERIALS AND METHODS

In the present study, timbers of jelutong (*Dyera costulata*) and khaya (*Khaya ivorensis*) were selected as samples. A total of four trees each of 10-year-old jelutong and 15-year-old khaya were obtained from plantation plots at Bukit Hari, Forest Research Institute Malaysia. The trees were considered as juvenile. Average heights of the jelutong and khaya trees were 7.3 and 19.3 m respectively. Average clear-bole heights were 5.2 and 9.6 m respectively. At breast height, diameters varied from 128 to 228 mm in jelutong and from 193 to 357 mm in khaya. Mean diameters of jelutong and khaya sample logs were 200 and 350 mm respectively. The logs were typically straight and slightly tapered.

Specimen preparation

Each tree was cut into logs of 2 m long, namely, bottom (b), middle (m) and top (t). From each log, sticks of 30 mm × 30 mm cross-section along the radial position (A to D) were cut as shown in Figure 1. Only the bottom logs were analysed due to the limitation of size. The sticks were stacked and air dried until constant weight is obtained. Each dried stick was cut and planed into specimens for static bending, compression parallel to grain, shear and tensile tests (BSI 1957).

Static bending test

The nominal size of the specimens was 20 mm × 20 mm × 300 mm. Force was applied based on three-point loading method with a span of

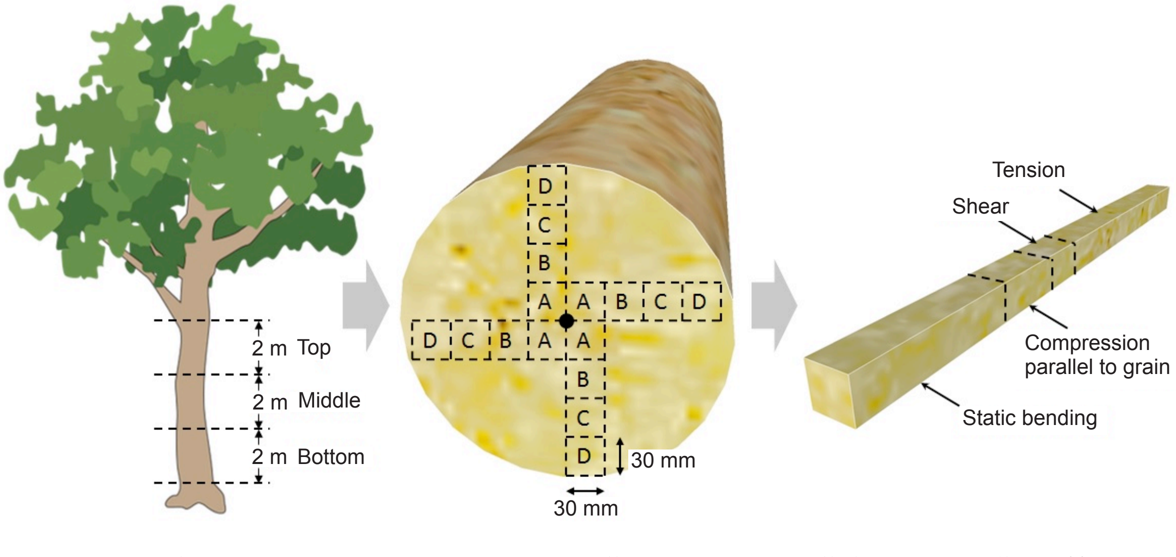

Figure 1 Cutting layout for preparation of specimens; illustration is partially by D Tracey (http://ian.umces.edu/imagelibrary/displayimage-6694.html)

280 mm. A constant loading speed was applied at 6.6 mm min^{-1}. MOE and MOR were calculated using the formulae:

$$\text{MOE} = \frac{1}{4}\frac{\Delta F}{\Delta l}\frac{s^3}{bd^3} \qquad (1)$$

$$\text{MOR} = \frac{3}{2}\frac{F_{bend}s}{bd^2} \qquad (2)$$

where $\frac{\Delta F}{\Delta l}$ = slope of the graph (N mm^{-1}), s = bending span (mm), b = width of the specimen (mm), d = thickness of the specimen (mm) and F_{bend} = maximum bending load (N).

Compression parallel to grain test

The nominal size of the specimens was 20 mm × 20 mm × 300 mm. Force was applied parallel to the grain. A constant loading speed was applied at 0.6 mm min^{-1}. Compressive strength parallel to the grain (σ_{comp}) was calculated using the formula:

$$\sigma_{comp} = \frac{F_{comp}}{A} \qquad (3)$$

where F_{comp} = maximum compressive load (N) and A = cross-sectional area normal to the direction of load (mm^2).

Shear parallel to grain test

The nominal size of the specimens was 20 mm × 20 mm × 20 mm. Force was applied with the plane of shearing parallel to the grain. A constant loading speed was applied at 0.6 mm min^{-1}. Shear strength parallel to the grain (τ) was calculated using the formula:

$$\tau = \frac{F_{shear}}{A} \qquad (4)$$

where F_{shear} = maximum shearing load (N) and A = area of shear (mm^2).

Tension parallel to grain test

The nominal length of the specimens was 300 mm. The specimens were flat shoulders-type with nominal width and thickness of 20 mm and 6 mm respectively. The gauge section in between was cut to a smaller width of 3 mm so that failure could occur within the area. The specimen was held in wedge-type grips. Force was applied parallel to the grain at a constant speed of 1.27 mm min^{-1}. Tensile strength parallel to the grain ($\sigma_{tensile}$) was calculated using the formula:

$$\sigma_{tensile} = \frac{F_{tensile}}{A} \qquad (5)$$

where $F_{tensile}$ = maximum tensile load (N) and A = cross-sectional area normal to the direction of load at which the failure occurred (mm^2).

Janka hardness test

The test was conducted using the specimens of static bending test. A constant force of 6.35 mm min^{-1} was applied using a test jig with a semicircular-end steel bar of 11.28 mm diameter. The load corresponding to the penetration depth of 5.64 mm was recorded as the Janka hardness value.

Specific gravity

The nominal size of the specimens was 20 mm × 20 mm × 60 mm. Specific gravity (SG) was calculated using the formula:

$$\text{SG} = \frac{m_{od}}{V}\frac{1}{\rho_{H_2O}} \qquad (6)$$

where m_{od} = oven-dry mass of the specimen (kg), V = volume of the specimen at test (m^3) and ρ_{H2O} = density of water (kg m^{-3}).

RESULTS AND DISCUSSION

Results for the mechanical properties tests were adjusted to the targeted reference condition of 12% moisture content. Table 1 shows the percentage changes of mechanical properties of the samples per 1% reduction in moisture content (Desch & Dinwoodie 1996). The average values are summarised in Tables 2 and 3. Jelutong (Lee et al. 1993) and khaya (Ani & Nordahlia 2009) had MOR values of 50 and 77 N mm^{-2}, MOE of 8100 and 7667 N mm^{-2}, compressive strength of 27 and 37 N mm^{-2} and shear strength of 5.8 and 11 N mm^{-2} respectively. Even under controlled sampling, some deviations in the measurements

Table 1 Percentage change in strength and stiffness per 1% change in moisture content in khaya (*Khaya ivorensis*) and jelutong (*Dyera costulata*)

Mechanical property	Moisture range (%)		
	6–10	12–16	20–24
Modulus of elasticity	0.21	0.18	0.15
Modulus of rupture	4.2	3.3	2.4
Compression	2.7	2.0	1.4
Hardness	0.058	0.053	0.045
Shear	0.70	0.53	0.36

were expected. Divergence of the ripping axis was the main factor that affected accuracy of the results. Misalignment during ripping of the logs placed the samples in inaccurate peripheral positions, particularly with tapered and curved logs. Nevertheless, we obtained some noticeable patterns in the mechanical properties relative to the radial and vertical positions in a tree.

Radial variations

Variations in MOR and MOE of jelutong were consistent with lowest values near the pith and increased towards the bark (Table 3). However, these variations were not consistent in khaya. The highest MOR was obtained near the pith but the subsequent position had the lowest. Results of the compression and tension parallel to grain tests were similar. There were no specific patterns for khaya, but jelutong showed increasing values from pith to bark.

A consistent pattern was observed from the results of shear parallel to the grain test of both jelutong and khaya (Tables 2 and 3). The values steadily increased from pith towards bark. Janka hardness test showed a similar pattern to specific gravity test. For khaya, the lowest values of hardness and specific gravity were obtained from the near-pith section with an increase at the intermediate region. The values decreased towards the bark and again increased to the highest level at the near-bark section. As for jelutong, hardness and specific gravity were lowest near the pith and increased towards the bark.

Vertical variations

Jelutong showed consistent variations in MOR and MOE values in vertical positions (Table 3). Highest values were obtained from the bottom logs whereas the lowest values were obtained from the middle. MOR and MOE values of khaya were not consistent but three trees showed lowest MOR values in the middle log.

Compression and tension parallel to grain tests of jelutong showed the lowest values in the middle logs (Table 3). The highest values were observed from the bottom logs. Similarly, for khaya, tension parallel to grain test was the lowest in the middle logs. However, compression test for khaya did not show any consistent pattern.

Khaya had the lowest shear strength in the bottom log (Table 2). On the other hand, jelutong had the highest values in the bottom logs. Janka hardness test of jelutong showed that the highest and lowest values were in the bottom and middle logs respectively. Specific gravity of jelutong showed the highest values in the bottom log. No specific patterns were observed for Janka hardness and specific gravity of khaya.

CONCLUSIONS

High strength and uniform mechanical properties were two of the most desired timber characteristics for plantation trees. Mechanical properties of jelutong and khaya along the radial and vertical positions were not symmetry. Jelutong showed more consistent patterns than khaya. Generally, increases in strength and specific gravity were observed from pith to bark sections. In the vertical analyses, the highest values were obtained in the bottom logs. The lowest values were mostly obtained in the middle logs. Based on more data in the future, and using statistical projection, it will be possible to determine the optimum age for harvest to ensure superior characteristics of timber.

Table 2 Mechanical properties of 15-year-old khaya

Mechanical property		Khaya (*Khaya ivorensis*)				
		Radial			Vertical	
		At test (17% MC)	Estimated at 12% MC		At test (17% MC)	Estimated at 12% MC
Modulus of rupture (N mm^{-2})	A	74.8 (71.5–78.1)	87.6 (83.8–91.5)	b	71.5 (61.2–79.3)	83.8 (71.6–92.9)
	B	70.4 (64.0–82.4)	82.4 (75.0–96.5)	m	67.5 (63.6–70.5)	79.1 (74.5–82.5)
	C	70.6 (58.7–75.7)	82.6 (68.7–88.6)	t	82.5 (73.4–96.4)	96.6 (85.9–112.9)
	D	71.1 (60.0–84.5)	83.3 (70.3–99.0)	-	-	-
Modulus of elasticity (N mm^{-2})	A	7015 (6608–7421)	7077 (6667–7487)	b	7891 (6890–9454)	7961 (6951–9538)
	B	7583 (6944–8146)	7650 (7006–8218)	m	7516 (7165–7760)	7583 (7229–7829)
	C	7907 (6880–9668)	7977 (6941–9754)	t	8286 (7566–9152)	8359 (7634–9234)
	D	7914 (6761–9847)	7984 (6821–9934)	-	-	-
Compressive strength parallel to grain (N mm^{-2})	A	35.3 (34.5–36.1)	38.9 (38.0–39.8)	b	33.6 (30.3-36.7)	37.0 (33.3-40.3)
	B	32.4 (26.9–39.6)	35.6 (29.6-43.6)	m	32.0 (29.2-38.4)	35.2 (32.1-42.3)
	C	33.1 (28.7–35.4)	36.4 (31.6–39.0)	t	34.9 (23.0–44.7)	38.4 (25.3–49.2)
	D	34.4 (32.1–39.0)	37.8 (35.3–42.9)	-	-	-
Shear strength parallel to grain (N mm^{-2})	A	9.6 (9.1–10.2)	9.9 (9.3–10.5)	b	10.2 (9.4–11.6)	10.4 (9.7–11.9)
	B	10.0 (8.4–12.2)	10.2 (8.6–12.5)	m	10.6 (9.7–11.7)	10.9 (9.9–12.0)
	C	9.9 (9.2–11.0)	10.2 (9.4–11.2)	t	11.6 (10.6–13.3)	11.9 (10.8–13.6)
	D	10.6 (9.9–11.7)	10.9 (10.2–12.0)	-	-	-
Tensile strength parallel to grain (N mm^{-2})	A	67.8 (66.7–68.8)	67.8 (66.7–68.8)	b	78.6 (71.0–84.0)	78.6 (71.0–84.0)
	B	78.4 (73.0–84.6)	78.4 (73.0–84.6)	m	66.3 (53.4–81.1)	66.3 (53.4–81.1)
	C	75.9 (57.3–90.8)	75.9 (57.3–90.8)	t	88.1 (84.9–91.3)	88.1 (84.9–91.3)
	D	81.0 (74.1–92.3)	81.0 (74.1–92.3)	-	-	-
Janka hardness (N)	A	2762 (2519–3005)	2769 (2526–3013)	b	2764 (2163–3194)	2771 (2169–3202)
	B	2741 (2149–3280)	2748 (2154–3289)	m	2835 (2642–2965)	2842 (2649–2973)
	C	2692 (2119–2987)	2699 (2125–2995)	t	3083 (2612–3640)	3091 (2619–3649)
	D	2867 (2338–3284)	2874 (2344–3292)	-	-	-
Specific gravity	A	0.415 (0.394–0.435)		b	0.450 (0.418–0.476)	
	B	0.445 (0.410–0.480)		m	0.461 (0.436–0.479)	
	C	0.444 (0.407–0.484)		t	0.459 (0.434–488)	
	D	0.465 (0.434–0.492)		-	-	-

A–D = radial positions as shown in Figure 1, positions in a tree: t = top, m = middle, b = bottom; MC = moisture content; figures in parentheses are the ranges of minimum and maximum values

Table 3 Mechanical properties of 10-year-old jelutong

Mechanical property	Jelutong (*Dyera costulata*)					
	Radial			Vertical		
		At test (14% MC)	Estimated at 12% MC		At test (14% MC)	Estimated at 12% MC
Modulus of rupture (N mm^{-2})	A	45.4 (39.9–49.0)	48.5 (42.5–52.3)	b	52.1 (44.8–55.9)	55.6 (47.8–59.7)
	B	53.0 (46.5–58.0)	56.6 (49.6–61.8)	m	46.9 (41.9–48.9)	50.0 (44.7–52.2)
	C	60.2 (52.0–65.0)	64.2 (55.5–69.4)	t	49.4 (43.3–52.3)	52.8 (46.2–55.9)
Modulus of elasticity (N mm^{-2})	A	5419 (4515–5891)	5439 (4531–5912)	b	6555 (5591–6978)	6579 (5611–7003)
	B	6578 (5950–7141)	6601 (5971–7166)	m	5948 (5481–6387)	5970 (5500–6410)
	C	8064 (6650–9624)	8094 (6674–9659)	t	6243 (5611–6679)	6265 (5631–6703)
Compressive strength parallel to grain (N mm^{-2})	A	23.9 (20.3–25.3)	24.9 (21.1–26.3)	b	28.1 (22.9–31.2)	29.3 (23.8–32.5)
	B	28.6 (23.7–31.9)	29.8 (24.7–33.2)	m	26.2 (23.8–27.6)	27.2 (24.8–28.7)
	C	33.1 (29.8–35.0)	34.5 (31.0–36.4)	t	27.6 (24.5–30.0)	28.7 (25.5–31.2)
Shear strength parallel to grain (N mm^{-2})	A	5.9 (5.4–6.4)	6.0 (5.4–6.4)	b	6.6 (6.0–6.9)	6.7 (6.0–6.9)
	B	6.7 (6.0–7.2)	6.7 (6.1–7.3)	m	6.2 (5.7–6.8)	6.3 (5.8–6.9)
	C	7.4 (6.5–8.4)	7.5 (6.6–8.5)	t	6.3 (5.5–6.6)	6.3 (5.6–6.7)
Tensile strength parallel to grain (N mm^{-2})	A	55.3 (47.4–62.7)	55.3 (47.4–62.7)	b	66.2 (58.4–72.1)	66.2 (58.4–72.1)
	B	65.1 (60.6–71.3)	65.1 (60.6–71.3)	m	54.9 (47.7–60.4)	54.9 (47.7–60.4)
	C	80.2 (73.0–87.5)	80.2 (73.0–87.5)	t	60.5 (54.0–65.9)	60.5 (54.0–65.9)
Janka hardness (N)	A	1266 (1142–1431)	1267 (1143–1432)	b	1525 (1255–1684)	1527 (1256–1686)
	B	1498 (1292–1791)	1500 (1294–1793)	m	1297 (990–1487)	1299 (991–1489)
	C	2004 (1662–2356)	2006 (1664–2359)	t	1309 (1018–1500)	1311 (1019–1502)
Specific gravity	A	0.297 (0.275–0.313)		b	0.333 (0.305–0.345)	
	B	0.336 (0.314–0.360)		m	0.305 (0.290–0.326)	
	C	0.373 (0.335–0.414)		t	0.305 (0.271–0.324)	

A–D = radial positions as shown in Figure 1, positions in a tree: t = top, m = middle, b = bottom; MC = moisture content; figures in parentheses are the ranges of minimum and maximum values

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REFERENCES

Ani S & Lim SC. 1993. Variation in specific gravity of five-year-old *Acacia mangium* from the Batu Arang plantation, Selangor, Malaysia. *Journal of Tropical Forest Science* 6: 203–206.

Ani S & Nordahlia AS. 2009. Wood properties of plantation species from rooted cuttings. Poster presented at the 7th Pacific Regional Wood Anatomy Conference. 3–5 August 2009, Kuala Lumpur.

BSI (British Standards Institution). 1957. *BS 373. Methods of Testing Small Clear Specimens of Timber*. BSI, London.

Desch HE & Dinwoodie JM. 1996. *Timber—Structure, Properties, Conversion and Use*. Seventh edition. McMillan, Basingstoke.

Lee YH, Engku ARC & Chu YP. 1993. *The Strength Properties of Some Malaysian Timbers*. Timber Trade Leaflet No. 34. Malaysian Timber Industry Board, Kuala Lumpur.

Lim SC & Gan KS. 2000a. Density and anatomical features of an eight-year-old sentang tree. *Journal of Tropical Forest Products* 6: 119–123.

Lim SC & Gan KS. 2000b. Some physical properties and anatomical features of 14-year-old *Acacia mangium*. *Journal of Tropical Forest Products* 6: 206–213.

Lim SC & Gan KS. 2011. Wood anatomy and quality. Pp 7–22 in Lim SC et al (eds) *Properties of Acacia mangium Planted in Peninsular Malaysia*. Forest Research Institute Malaysia, Kepong.

Moya R, Perez LD & Arce V. 2003. Wood density of *Tectona grandis* at two plantation spacings in Costa Rica. *Journal of Tropical Forest Products* 9: 153–161.

Trockenbrodt M, Fruhwald A & Helmer T. 2000. Wood density and elastomechanical properties of *Macaranga gigantifolia* and *M. hypoleuca* from Sabah, Malaysia. *Journal of Tropical Forest Products* 6: 62–67.