Effect of Radial Growth Rate on Wood Properties Variation of Sentang (*Azadirachta excelsa*) Tree Planted in Kelantan, Malaysia

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Properties of Sentang wood planted in Kelantan, Malaysia, were studied, focusing on the effect of radial growth rate on variation in the fiber and vessel element dimensions, moisture content, density, shrinkage, bending, and compression strength at the breast height of the tree. The trees were categorized into slow-, average-, and fast-growth categories, based on their breast height diameter and standard deviation. The variations in properties were then examined from the pith to the bark. The fiber length and diameter tend to decrease until a certain distance from the pith, followed by an increase toward the bark. Contrastingly, the vessel element length and diameter tend to increase until a maximum size is reached and then exhibit a relatively constant size toward the bark. The fast-growing trees tended to have longer and larger fibers, while the slow-growing trees tended to have longer and larger vessel elements. In addition, the fast-growing trees tended to have a higher green moisture content and shrinkage, lower density, lower modulus of rupture (MOR), and lower compression strength. The results revealed that growth rate seems to influence the modulus of elasticity (MOE) less than the MOR and compression strength.

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INTRODUCTION

Forest plantations are defined based on the planting or seeding of forest stands as a process of afforestation or reforestation. Forest plantation establishment usually involves a fast-growing monoculture or indigenous species. The selected species are generally planted in uniform-spaced rows, resulting in an even-age stand, and the trees are treated using similar silviculture practices throughout all the plantation areas (Evans 1999; Kanowski 2001; Carle *et al*. 2002).

In Malaysia, forest plantation was introduced, following right after Japan, the United States, China, India, and the Russian Federation, as a strategy for overcoming the shortage of wood resources and maintaining the expansion of downstream wood-based industries. It was reported that the Forest Research Institute Malaysia (FRIM) started a trial of forest plantation plots in the 1920s using various fast-growing species (Selvaraj and

Muhammad 1980; Krishnapillay 2002). However, the first large-scale commercial forest plantation emerged with the proposed setting up of integrated pulp and paper mills in Peninsular Malaysia in 1967 using fast-growing tropical pine and araucaria species (Freezailah and Fielding 1971). Subsequently, the Malaysian government has attempted to complement the log supply from the natural forest by establishing forest plantations. Such activity peaked in 1990 when the Malaysian government introduced a large-scale commercial forest plantation development program using several fast-growing timber species, including Acacia (*Acacia mangium*), Rubberwood (*Hevea brasiliensis*), Kelempayan (*Neolamarckia cadamba*), Batai (*Paraserianthes falcataria*), Sentang (*Azadirachta excelsa*), Khaya (*Khaya ivorensis*), Binuang (*Octomeles sumatrana*), and Teak (*Tectona grandis*).

Therefore, besides Teak, Sentang was mentioned to have great potential as a wood resource from forest plantations due to its substantial coverage of 8,000 ha in Peninsular Malaysia (Huat *et al*. 2003; Hashim *et al*. 2015). Several researchers have reported the characteristics of Sentang, including the morphology of the tree and some properties of the wood in general. Sentang wood was identified as diffuse-porous with a wood density range of 550 to 780 kg/m^3 and is categorized as light-hardwood in Malaysia. The wood has been used for furniture and lightweight wooden construction (Noraini 1997; Wong *et al*. 2002). In addition, some research groups have attempted to investigate the properties of Sentang wood in more detail. However, these studies focused more on the properties of young-age Sentang trees (Trockenbrodt *et al*. 1999; Rafeadah and Rahim 2007; Nordahlia *et al*. 2011; Nordahlia *et al*. 2014; Wahyudi *et al*. 2016), lacking analysis for mature trees.

In contrast, it is widely accepted that in any given stand, the radial growth rate of the individual tree varies according to age, relationships with neighboring trees, and local site factors (Stoll and Newbery 2005; Baribault *et al*. 2012; Stephenson *et al*. 2014). Thus, even in the same site, each tree would exhibit different radial growth rates, and this could affect the properties of the wood. Generally, growth ring width, structure, and uniformity affect the wood properties that determine the wood quality, and each can be changed with a variation in radial growth rate (Bendtsen and Senft 1986; de Kort *et al*. 1991; Herman *et al*. 1998). It was reported that a faster-growth tree tends to have a wider growth ring and lower density with a significant amount of juvenile wood (Carino and Biblis 2009; Karlsson *et al*. 2013; Carrasco *et al*. 2014). Thus, the wood would have characteristics unsuitable for high-quality timber products. However, exceptions were found in some trees, such as diffuse-porous hardwood, for which it was reported that the radial growth rate slightly influences the wood properties (Zhang 1995; Naji *et al*. 2011).

As mentioned above, the previous studies focused more on the wood properties of young-age Sentang trees. It is well known that wood from young-age trees has different properties from mature trees. Thus, more samples from mature trees must be studied to draw general conclusions regarding the properties of Sentang wood. In addition, the wood reported has a potential as raw material for wood-based composite production (Iswanto *et al*. 2010), emphasizing the need to elucidate its properties for a broader range of end-use products. In this regard, this study was conducted to investigate the properties of mature Sentang wood and focused on examining the radial variation in the anatomical, physical, and mechanical properties of the wood at the breast height of the tree. Studying these properties is vital, as these properties are essential indicators for wood used in furniture and wood-based composite applications, as well as crucial determinants of suitability for structural purposes.

EXPERIMENTAL

Field Site

The site was located in Jeli, Kelantan, Malaysia. Four thousand saplings from Perak, Malaysia, were used to establish a small-scale Sentang plantation in 1995. Light silvicultural treatment was conducted. However, the plantation has been unmanaged since 2004, and some trees have been harvested for domestic purposes.

Tree Inventory

Thirty trees, aged 26 years old, were randomly selected from a 1-hectare plot containing approximately 300 trees. The diameter of the trees at breast height (DBH) was then measured. The trees were categorized into slow-, average-, and fast-growth categories based on their average DBH (DBH_{ave}) and standard deviation (SD). The slow-growth trees had $DBH < DBH_{ave} - SD$. The average-growth trees had $DBH_{ave} - SD \leq DBH \leq DBH_{ave} + SD$. Meanwhile, the fast-growth trees had $DBH > DBH_{ave} + SD$. The results showed that the slow-growth trees had a DBH below 310 mm, the average-growth trees had a DBH from 310 to 470 mm, and the fast-growth trees had a DBH above 470 mm.

Sample Preparation

A total of three trees with the DBH of 300, 390, and 480 mm were selected from the plot for slow-, average- and fast-growth trees, respectively, and then harvested at 500 mm above the ground. After harvesting, the stems were cross-sectionally cut at the breast height into 50 and 150-mm-thick discs for the anatomical, physical, and mechanical properties examination, respectively. The Eastside of the 150-mm-thick disc was processed into consecutive sample sticks with a dimension of 20 (T) × 20 (R) × 150 (L) mm^3 from the pith to the bark. The sample stick was then processed into two cube samples of 20 (T) × 20 (R) × 20 (L) mm for shrinkage and compression strength examination. The rest of the sample stick was processed into three static bending samples with a dimension of 20 (T) × 5 (R) × 80 (L) mm^3. In addition, the 50-mm-thick disc was processed similarly into sample sticks and two cube samples with a dimension of 20 (T) × 20 (R) × 20 (L) mm^3 for the anatomical properties evaluation. The cutting patterns for sample preparation are illustrated in Fig. 1.

Anatomical Properties Evaluation

The latewood of the cube samples was cut into match sizes and macerated according to the Schultze method using 6 g of potassium chlorate and 100 mL of 35% nitric acid solution. Before microscopic observation, the macerated samples were crumbled and soaked in Safranin dye. A total of 50 latewood fiber and 30 vessel element images were randomly captured at 40 times magnification using a digital microscope (Leica DM750, Wetzlar, Germany). The variation in the fiber length and diameter and the vessel element length and diameter at the breast height of the tree was measured from the pith to the bark using ImageJ software (NIH, 1.53k, Bethesda, MD, USA). In addition, scanning electron microscopy (SEM) images of the cross-section of the cube sample were captured using SU3500, Hitachi High-Tech Corporation, Tokyo, Japan, to identify the morphological appearance of the cells.

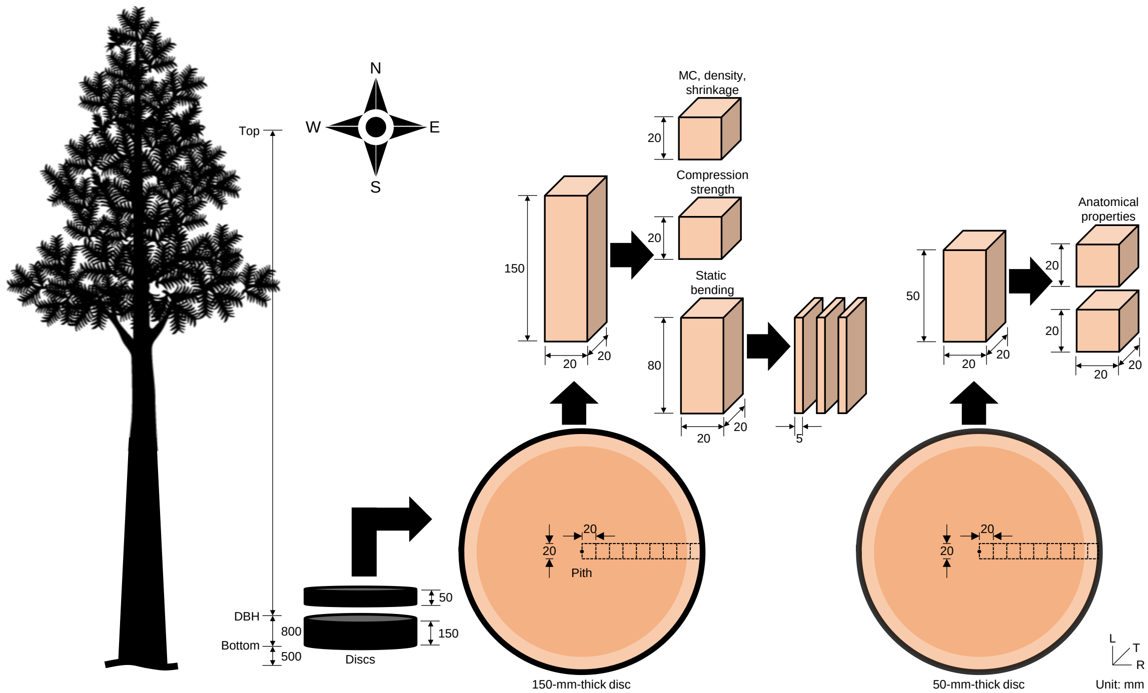

Fig. 1. Cutting patterns of the samples used in this study

Shrinkage Measurement

While air-dried, the change in cube sample weight and dimension in the longitudinal, radial, and tangential directions were periodically measured until a constant weight was achieved. After air-drying, the cube samples were further dried for another 24 h at a temperature of 40 °C in the oven, and the weight and dimension were measured again. The shrinkage in the tangential, radial, and longitudinal directions was calculated using the following Eq. 1,

$$\alpha_M = \frac{l_0 - l_M}{l_0} \times 100\% \tag{1}$$

where α_M is shrinkage at M% MC, l_0 is a dimension at green MC, and l_M is a dimension at M% MC. The shrinkage data were then plotted over its MC, and the shrinkage at 12% MC was then calculated based on the exponential correlation between the shrinkage and its MC.

Green MC and Density Measurement

After shrinkage measurement, the samples were oven-dry at the temperature of 103 °C for 24 h, and the MC was then calculated using the following Eq. 2,

$$MC = \frac{m_1 - m_0}{m_0} \times 100\% \tag{2}$$

where m_1 and m_0 are green mass and mass of the samples after oven-dry, respectively. The green wood density was defined as the ratio of the green mass of the sample over its volume. While the air-dry wood density was determined from the static bending test sample.

Static Bending Test

The test was conducted using a Universal Testing Machine (UTM) with an effective span of 70 mm. A load was then applied at a 1 mm/min speed to determine the modulus of rupture (MOR) and modulus of elasticity (MOE) of the sample. The MOR and MOE were calculated using the following equations,

$$MOR = \frac{3PL}{2bh^2} \tag{3}$$

$$MOE = \frac{P_1 L^3}{4d_1 bh^3} \tag{4}$$

where P is the maximum load, L is the span, b and h are the width and thickness of the sample, respectively. While P_1 and d_1 are load and deflection at the proportional limit, respectively.

Compressive Strength Test

Using the UTM, a load was applied at a transverse section of the sample surface with a 1 mm/min loading speed. The maximum load was recorded to calculate the compressive strength (F) parallel to the grain of the sample using the following equation,

$$F = \frac{P}{A} \tag{5}$$

where P is the maximum load, A is the cross-section area of the sample.

RESULTS AND DISCUSSION

Fiber Dimensions

Figure 2 demonstrates the radial variation of the fiber dimensions at the breast height of the trees. The fiber length near the pith generally has a shorter dimension due to the presence of juvenile wood (Evans *et al*. 2000). Another study also found that the fiber length of some fast-growing tropical species tends to have shorter fiber length near the pith and increases toward the bark (Honjo *et al*. 2005; Nugroho *et al*. 2012; Ishiguri *et al*. 2016). Interestingly, the figure illustrates a pattern where the fiber length initially decreases until a certain distance from the pith, followed by an increase towards the bark. However, the underlying reason for this pattern remains unclear. In this study, the average fiber length was 870, 802, and 1042 µm for slow-, average- and fast-growth trees, respectively, suggesting that the fast-growing tree had a longer fiber than the other categorized trees. The results were similar to the previous findings, mentioning that the average fiber length of a 10-year-old Sentang grown from a seedling in Selangor, Malaysia, was 975 µm (Nordahlia *et al*. 2011).

For the fiber diameter, the figure also shows a similar tendency to the fiber length. The fiber diameter of all the categorized trees initially decreased until a certain distance from the pith, followed by an increase towards the bark. In this study, the average fiber diameter was 16.8, 18.1, and 24.4 µm for slow-, average- and fast-growth trees, respectively. The results revealed that the fast-growth tree had the largest diameter among the categorized trees. This finding was slightly higher than the previous study that reported the average fiber diameter of the 10-year-old Sentang was 16.8 µm (Nordahlia *et al*. 2011).

From the results mentioned above, it was clear that the fast-growing tree tended to have a longer and larger fiber than the other categorized trees. This result seems opposed to the other findings, mentioning that a faster-growth tree tends to have a shorter fiber due to an increased cell division rate in the cambium (Zobel and van Buijtenen 1989; Roque and Fo 2007). However, an exception was found in diffuse-porous hardwood, such as fast-growth Eucalypts, which tend to have a longer fiber (Wilkes and Abbott 1983).

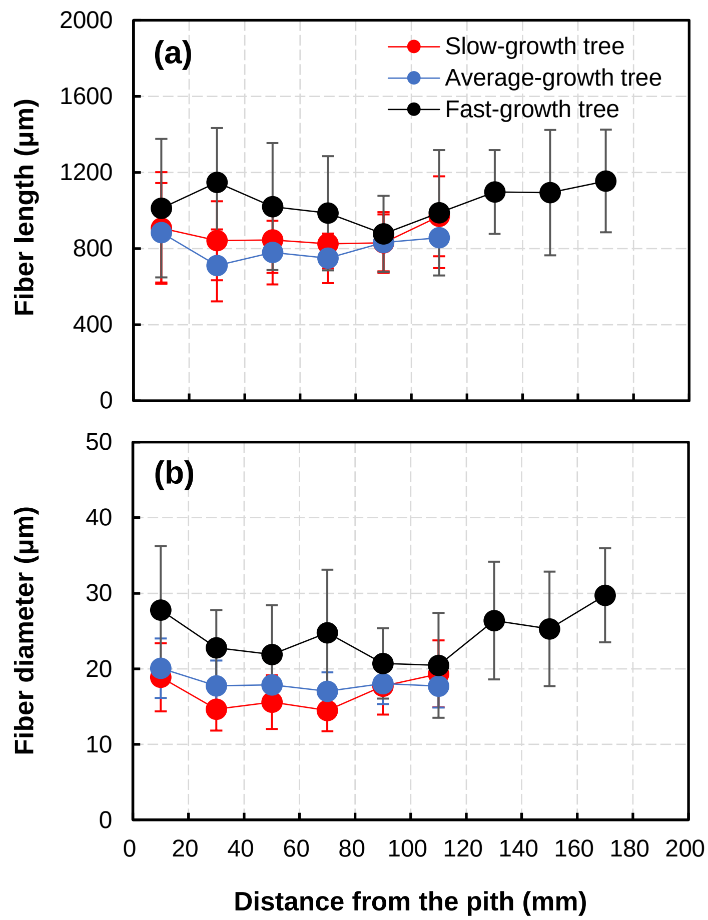

Fig. 2. Radial variation of the fiber length (a) and diameter (b) at the breast height of the trees. The fiber length and diameter values are the average value of 50 latewood fibers. The error bar indicates the SD.

Vessel Element Dimensions

Figure 3 illustrates the radial variation of the vessel element dimensions at the breast height of the trees. As shown in the figure, the vessel element length tends to increase gradually until a maximum length is reached and then exhibits a relatively constant length toward the bark. Several authors also reported that the vessel element length of some species tends to increase along the radial direction of the tree (Chowdhury *et al*. 2009; Tsuchiya and Furukawa 2009). In this study, the average vessel element length was 590, 571, and 565 µm for slow-, average- and fast-growth trees, respectively. The finding indicated that the slow-growth tree has a longer vessel element than the other categorized trees. The figure also shows that the vessel element diameter has a similar tendency as the length.

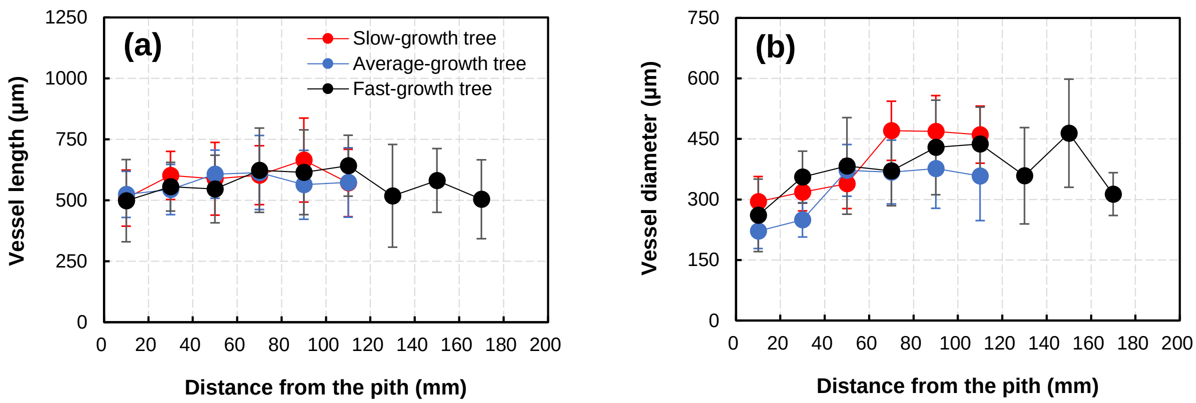

Fig. 3. Radial variation of the vessel element length (a) and diameter (b) at the breast height of the trees. The vessel length and diameter values are the average value of 30 vessel elements. The error bar indicates the SD.

This tendency was confirmed by the SEM image of the sample cross-section, as shown in Fig. 4, which demonstrates vessel element of the sample at 20 mm from the pith has a relatively larger size than that at 120 mm from the pith. Several authors also reported that the vessel element diameter of some fast-growing species tends to increase along the radial direction of the tree (Ishiguri *et al*. 2009; Nugroho *et al*. 2012). In this study, the average vessel element diameter at the breast height of the slow-, average-, and fast-growth trees was 392, 324, and 375 µm, respectively. The results were much higher than the 10-year-old Sentang, with an average vessel diameter of 140 µm (Nordahlia *et al*. 2011).

In addition, the findings suggested that the fast-growth tree tends to have a shorter and smaller vessel element than the other categorized trees, which is likely due to an increased cell division rate in the cambium. It was believed that when growth is rapid, the cambial initials divide before reaching their potential length (Zobel and van Buijtenen 1989).

From the results mentioned above, it was clear that the fast-growth tree tended to have a longer and larger fiber, while the slow-growth tree tended to have a longer and larger vessel element.

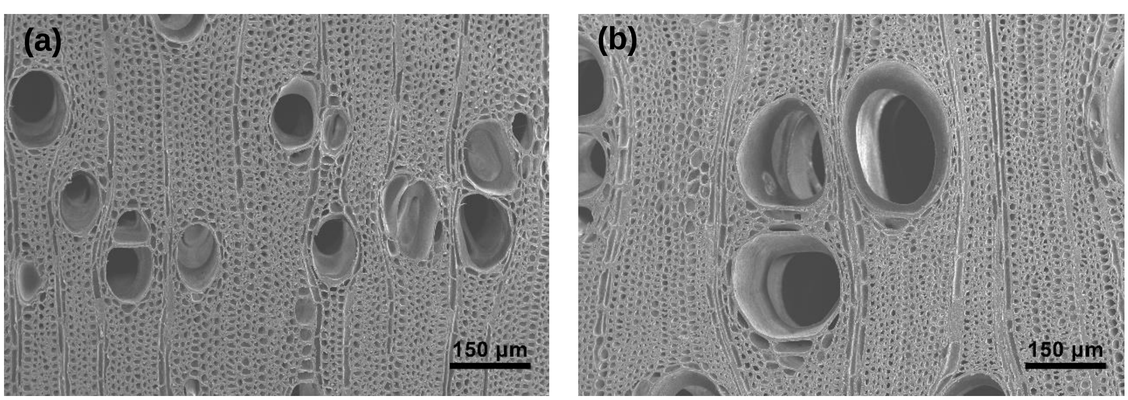

Fig. 4. SEM image of the sample cross-section at 20 mm (a) and 120 mm (b) from the pith of the slow-growth tree

Wood MC and Density

Table 1 presents the radial variation of the green wood MC, green wood density, and air-dry wood density at the breast height of the trees. The results showed that the green wood MC tends to decrease toward the bark, except for the fast-growth tree.

Table 1. Radial Variation of the Green MC, Green Density, and Air-dry Density at the Breast Height of the Trees

Tree Category	Distance from the Pith (mm)	Green MC (%)	Green Density (kg/m^3)	Air-dry Density (kg/m^3)
Slow-growth tree	0 to 20	-	-	509 (47)
	20 to 40	47.5	654	531 (16)
	40 to 60	42.8	680	570 (33)
	60 to 80	43.0	665	570 (20)
	80 to 100	43.8	703	590 (22)
	100 to 120	36.7	704	608 (12)
Average-growth tree	0 to 20	-	-	528 (77)
	20 to 40	46.4	673	556 (23)
	40 to 60	45.7	670	544 (13)
	60 to 80	43.9	706	593 (12)
	80 to 100	40.6	708	589 (13)
	100 to 120	35.3	653	584 (31)
	120 to 140	34.9	664	584 (14)
Fast-growth tree	0 to 20	-	-	500 (14)
	20 to 40	-	-	474 (17)
	40 to 60	45.8	617	527 (5)
	60 to 80	45.2	631	523 (21)
	80 to 100	48.9	634	499 (35)
	100 to 120	49.3	616	503 (35)
	120 to 140	-	-	607 (76)
	140 to 160	55.8	724	560 (40)
	160 to 180	58.8	696	541 (24)
	180 to 200	49.2	687	574 (63)
The number in the bracket shows the SD, -: measurement not conducted				

The variations in wood MC along the radial direction are generally related to the presence of heartwood and sapwood. It is generally known that heartwood often has lower MC than sapwood. Thus, the green wood MC typically tends to increase toward the bark. However, several authors reported that the green wood MC for some fast-growing species, including *Cedrela odorata*, *Acacia mangium,* and *Gmelina arborea*, was higher near the pith than the bark (Ofori and Brentuo 2005; Muñoz and Moya 2008). In this study, the average green wood MC at the breast height of the slow-, average-, and fast-growth trees was 42.7, 41.2, and 50.4%, respectively. These results suggested that the fast-growth tree tends to have a much higher green wood MC.

In contrast, the table shows that the green wood density tends to increase toward the bark, except for the average-growth tree. A similar tendency was also reported in the other fast-growing species, such as *Casuarina odorata* and *C. equisetifolia* (Ofori and Brentuo 2005; Chowdhury *et al*. 2009). In this study, the average green wood density at the breast height of the slow-, average-, and fast-growth trees was 681, 679, and 658 kg/m^3, respectively. In addition, the table showed that the air-dry wood density at the breast height of all the categorized trees tends to increase toward the bark. In this study, the average air-dry wood density of the slow-, average- and fast-growth trees was 563, 568, and 530 kg/m^3, respectively. Similar to the other finding, these results indicated that the fast-growth tree tends to have a lower air-dry wood density (Carrasco *et al*. 2014). Various factors may affect the wood density, such as cell types and their proportion and size.

Shrinkage

Table 2 presents the radial variation of the wood shrinkage at an MC of 12% in the tangential, radial, and longitudinal directions. The results showed that the wood shrinkage in all directions tended to fluctuate from the pith toward the bark. As predicted, the wood shrinkage of all the categorized trees in the tangential direction was the highest compared to the other directions.

In this study, the average wood shrinkage for the slow-growth tree at a MC of 12% in the tangential, radial, and longitudinal directions was 2.80, 1.78, and 0.62%, respectively. For the average-growth tree, the average wood shrinkage was 3.18, 1.67, and 0.62% in the tangential, radial, and longitudinal directions, respectively. The fast-growth tree had an average wood shrinkage of 4.11, 2.35, and 0.95% in the tangential, radial, and longitudinal directions, respectively. The results indicated that the fast-growth tree had higher wood shrinkage despite having a lower density than the other categorized trees. Because wood density serves as an index of the cell wall substance of wood, it is understandable that wood shrinkage is closely related to wood density (Tsutsumi *et al*. 2020).

However, several studies reported that wood density less or moderately affects its shrinkage (Saranpaa 1992; Zhang *et al*. 1994). The close relationship between shrinkage and juvenile wood is also expected, as juvenile wood usually has a larger microfibril angle in the cell wall (Zobel and Sprague 1998), thus there is more considerable shrinkage than mature wood in the longitudinal direction. However, the results did not show a noticeable confirmation of this consensus.

The other factors, such as extractive content, probably have a more important effect on the shrinkage, as it reported that the extractive in the cell walls reduces the hygroscopicity of wood (Choong and Achmadi 1991). Nevertheless, further study is required to investigate the effect of radial growth rate on the microfibril angle and extractive content of Sentang.

Table 2. Radial Variation of the Wood Shrinkage at a MC of 12%

Tree Category	Distance from the Pith (mm)	Shrinkage (%)		
		Tangential	Radial	Longitudinal
Slow-growth tree	0 to 20	-	-	-
	21 to 40	2.58	1.60	0.73
	41 to 60	3.03	1.81	0.62
	61 to 80	3.04	1.70	0.68
	81 to 100	2.72	1.98	0.53
	101 to 120	2.64	1.83	0.56
Average-growth tree	0 to 20	-	-	-
	21 to 40	3.38	1.67	0.47
	41 to 60	3.70	1.40	0.49
	61 to 80	2.71	1.50	0.79
	81 to 100	3.13	1.94	0.72
	101 to 120	2.62	1.60	0.59
	121 to 140	3.56	1.89	0.68
Fast-growth tree	0 to 20	-	-	-
	21 to 40	-	-	-
	41 to 60	3.64	2.18	0.86
	61 to 80	3.67	2.29	1.04
	81 to 100	4.32	2.40	1.06
	101 to 120	3.41	2.38	0.85
	121 to 140	-	-	-
	141 to 160	3.15	2.47	0.98
	161 to 180	5.94	2.35	0.82
	181 to 200	4.65	2.35	1.04

-: measurement not conducted

Bending Properties and Compression Strength

Figure 5 illustrates the radial variation of the MOR, MOE, and compression strength at the breast height of the trees. The figure demonstrated that the MOR and MOE tended to increase until a maximum value was reached and then exhibited a relatively constant value toward the bark.

In this study, the average MOR and MOE of slow-, average-, and fast-growth trees were 87.4 and 8325, 86.4 and 8749, and 77.9 and 8428 N/mm^2, respectively. A slightly lower value was obtained from the previous study, which reported that the average MOR and MOE of Sentang were 60.0 to 83.9 and 6770 to 6862 N/mm^2, respectively (Noraini 1997).

The results showed that the fast-growing tree had a relatively similar MOE to the slow-growth tree; however, the tree tended to have a lower MOR than the other categorized trees. This result suggested that the growth rate has a minor influence on the MOE.

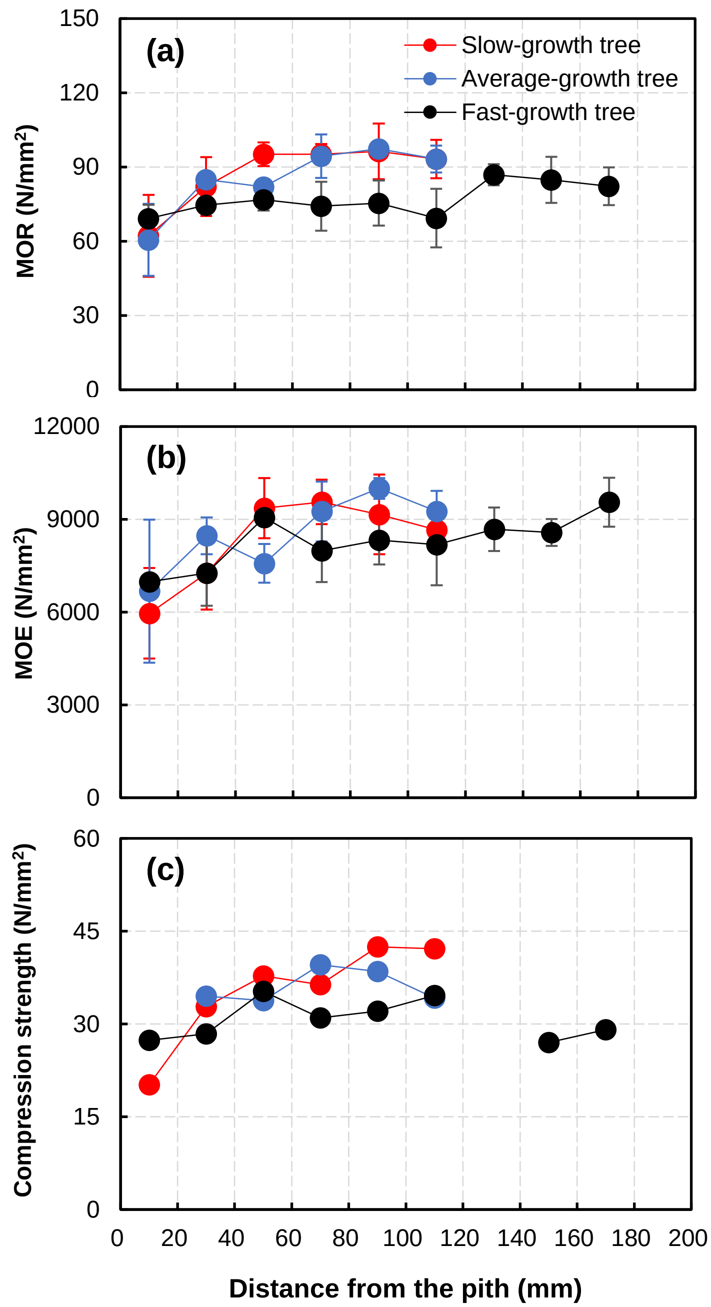

Fig. 5. Radial variation of the MOR (a), MOE (b), and compression strength (c) at the breast height of the trees. The MOR and MOE values are the average value of three samples, while the compression strength value was obtained from one sample. The error bar indicates the SD.

Similarly, the results showed that the compression strength at the breast height of the trees tended to increase until a maximum value was reached and then exhibited a relatively constant value toward the bark. In this study, the average compression strength of slow-, average-, and fast-growth trees was 35.3, 35.7, and 30.2 N/mm^2, respectively. A comparable result was obtained from the previous study, which reported that the average compression strength of Sentang was 31.0 to 42.0 N/mm^2 (Noraini 1997). The results revealed that the fast-growth tree showed lower compression strength than the other categorized trees.

From the results mentioned above, it was clear that the growth rate seems to have less influence on the MOE than MOR and compression strength. Another researcher also reported a similar result, mentioning that the MOE is remarkably less influenced by the growth rate than the MOR and compression strength (Zhang 1995). However, a study involving a larger sample size is required to establish the general validity of these findings.

CONCLUSIONS

In this study, Sentang trees planted in Kelantan, Malaysia, were categorized into slow-, average, and fast-growth trees. The trees were harvested, and the anatomical, physical, and mechanical properties of the wood at the breast height along the radial direction of the tree were then examined. The results were as follows.

1. The fiber length and diameter of all the categorized trees tended to decrease until a certain distance from the pith, followed by an increase toward the bark.
2. The vessel element length and diameter of all the categorized trees tended to increase until a maximum size was reached and then exhibited a relatively constant size toward the bark.
3. The fast-growth trees tended to have a longer and larger fiber, while the slow-growth trees tended to have a longer and larger vessel element.
4. The fast-growth trees tended to have a higher green moisture content and shrinkage, lower density, MOR, and compression strength.
5. The results revealed that growth rate seemed to have less influence on the MOE than MOR and compression strength.

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