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Stress wave velocity, basic density, and compressive strength in 34-year-old *Pinus merkusii* planted in Indonesia

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Abstract The relationship between the growth speed and wood properties of *Pinus merkusii* was investigated using 34-year-old trees planted in Indonesia in an attempt to promote the establishment of plantation of this species. The trees in the test plot were categorized as fast, middle, or slow growing according to the mean stem diameter and standard deviation in the plot. Five trees were selected from each category to investigate the effects of the growth rate on the wood properties [basic density (BD) and compressive strength parallel to the grain in a 5-mm-diameter core sample (CS)]. No significant correlation was recognized between the stem diameter and the stress wave velocity of trees. Clearly lower values of BD and CS were found in slow-growing trees than in fast- and middle-growing trees. The BD of xylem near the pith was reduced by extraction with organic solvent. BD after extraction and CS gradually increased from pith to bark. The results obtained in this study clarified that an early selection of trees with high BD is possible by using the BD after extraction at 4 cm from the pith.

Key words *Pinus merkusii* · Basic density · Compressive strength · Stress wave velocity · Early tree selection

Introduction

Pinus merkusii Junghuhn and de Vriese is widely distributed from Myanmar to Indochina, the northern half of Sumatra, and northern Luzon.[1] The tree is commonly planted in Southeast Asia.[2] The wood is used for construction, flooring, and boat building because it is fairly durable and heavy.[2]

Pinus merkusii is considered a fast-growing plantation species in Southeast Asia. A large tree grows from 50 to 70 m tall with a straight and cylindrical bole free of branches up to 15–25 m and an average diameter of 55 cm.[2] However, the rotation age on a *P. merkusii* plantation is not as early as that of fast-growing hardwood species, such as *Paraserianthes falcataria* and *Acacia mangium*, in tropical regions. A longer rotation period in plantation results in the conservation of forest and land. In addition, resin, a chemical raw material, is harvested from the xylem of this species. Resin tapping provides income before harvesting the wood for local people who live near the plantation area and prevents illegal logging. Thus, this tree is an important plantation species in Southeast Asia. However, limited information is available about the relationship between the growth and wood properties in *P. merkusii*.

The final objective of this study was to promote the establishment of plantation of this species. To achieve this final objective, in the present study, the relationship between growth and wood properties was examined for 34-year-old *P. merkusii* trees planted in Indonesia. Diameter, height, and stress wave velocity (SWV) in the longitudinal direction of stem, which is good predictor of the Young's modulus of logs, were measured. In addition, the radial variation of basic density (BD) and compressive strength (CS) parallel to grain were also determined by using core samples (5 mm in diameter) collected from 15 trees selected from an experimental stand. Based on the results obtained, the relationship between the growth and wood properties in *P. merkusii* is discussed.

Materials and methods

The experimental stand is located in an educational forest of Bogor Agricultural University, Gunung Walat, Skabumi, Indonesia (6°54′S, 106°49′E). Although the stand was established by planting seedlings in 1975, the seed source is

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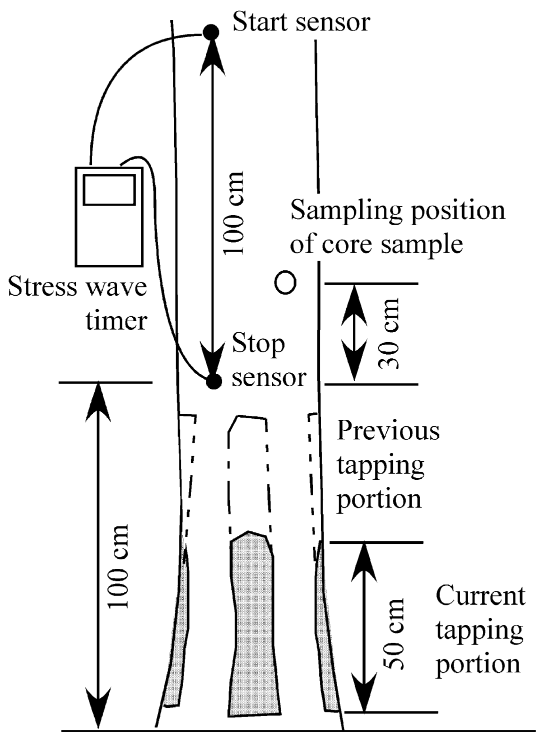

Fig. 1. Measurement of stress wave velocity and sampling of core sample. Bark and xylem (approx. 10 by 50 cm) had been removed for tapping (*gray color*). There were four tapping portions at the same height in a tree. Previous tapping portions (*dashed line*) were already covered with newly formed bark. All wood properties were measured at a sound part of the stem

unknown. A part of the xylem and bark of all stems in the stand had been partially removed by local people to collect resin. All wood properties were determined at the sound portion (Fig. 1).

A plot of 45 × 15 m was set in a stand. The diameter at 1.3 m above the ground, the height, and the stress wave velocity of standing trees were measured for all 33 trees in the plot. The stress wave velocity of trees was measured according to a method previously described.[3] The start and stop sensors were set at 1.0 and 2.0 m above ground level, respectively (Fig. 1). The stress wave propagation time in the longitudinal direction was measured six times and the mean value was used for calculating the SWV.

For determination of the BD and CS, trees in a stand were classified into three categories according to their growth rate: fast (larger than the average diameter plus one standard deviation), middle (with the average diameter), and slow (smaller than the average diameter minus one standard deviation).[3] Five randomly selected trees in each category were used for measuring the BD and CS. Core samples (5 mm in diameter) were collected from 1.3 m above ground level for the 15 selected trees. Two core samples were obtained from each selected tree. One core sample was used for measuring BD and the other core sample was used for measuring CS. The BD was measured every 1 cm from pith to bark. The BD was determined by dividing the oven-dried weight by the green volume

Table 1. Mean values (n = 33) of diameter, height, and stress-wave velocity of trees in a plot

Property	Mean	SD	Min	Max
Diameter (cm)	35.5	8.5	20.6	55.5
Height (m)	29.7	4.6	16.3	35.2
SWV (km/s)	4.39	0.32	3.76	5.12

SD, standard deviation; SWV, stress-wave velocity

measured by water displacement. To evaluate the effect of resin on BD, blocks were extracted with organic solvent (an ethanol–toluene solution). For determining the CS of core samples, the core samples were cut into pieces 5 mm wide in sequence from pith to bark, and CS was determined for the pieces using strength-testing equipment (Fractometer II, IML) as described in a previous study.[4]

The mean values of BD and CS were also calculated every 2 cm from pith to bark to clarify their radial variation. In addition, the radial variation in relation to relative distance from the pith was also determined according to a method described by Chowdhury et al.[5]

Results and discussion

Relationships between growth characteristics and SWV

The mean diameter, height, and SWV in the plot were 35.5 cm, 29.7 m, and 4.39 km/s, respectively (Table 1). Grabianowski et al.[6] reported that the mean SWV in 27-year-old trees of *P. radiata* was 3.13 km/s. Thus, SWV in 34-year-old *P. merkusii* showed larger values than those obtained from other *Pinus* species. Chauhan and Walker[7] also reported that the SWVs of 8-, 16-, and 25-year-old trees of *P. radiata* were 1.88, 2.38, and 2.88 km/s, respectively, suggesting that SWV tends to increase with increasing tree age. Thus, the tree age might be related to the higher SWV values obtained in 34-year-old *P. merkusii* compared to SWV obtained in other *Pinus* spp.[6,7]

Significant but weak negative correlation coefficients have been observed between stem diameter and SWV in softwood species.[7,8] In the present study, there was no significant correlation (r = 0.114, 5% level) between the stem diameter and SWV (Fig. 2). In contrast, a significant correlation was found between the stem diameter and tree height (Fig. 2). Thus, growth characteristics are closely related to each other.

Basic density

The mean BD was 0.53, 0.55, and 0.44 g/cm^3 for fast-, middle-, and slow-growing trees, respectively (Table 2). Ogata et al.[1] reported that the air-dry density for timber from Southeast Asia and the Western Pacific ranged from 0.50 to 0.85 g/cm^3. Our results obtained in fast- and middle-growing trees are similar to those reported by Ogata et al.[1]

Figure 3 shows the radial variation of BD in each growth category. In slow-growing trees, BD gradually increased

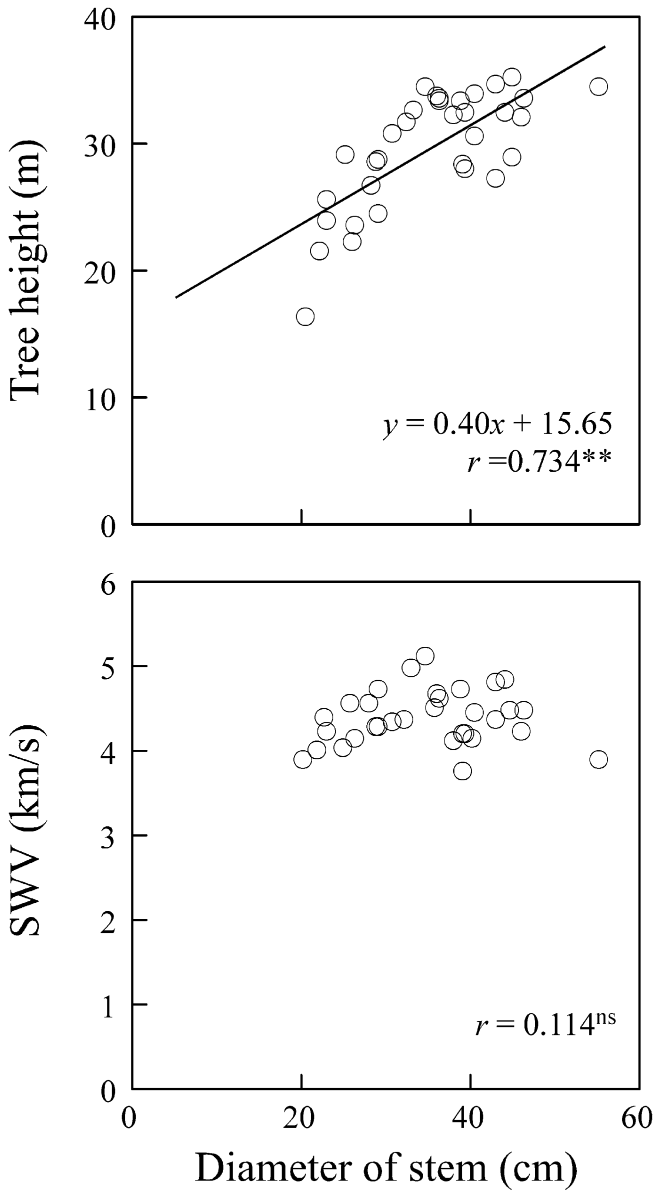

Fig. 2. Relationships between the stem diameter and tree height and stress wave velocity (*SWV*) of trees in a plot. Number of trees = 33. *r*, correlation coefficient; **, significant at the 1% level; *ns*, not significant

from pith to bark. This was also true for some trees in the fast- and middle-growing categories. However, the BD of other trees in the fast and middle categories showed the highest value in xylem near the pith. Zobel and van Buijtenen[9] reported that many resinous and phenolic deposits in wood greatly influence its density. The density of ponderosa pine (*Pinus ponderosa*) was reduced by 12% by removing extractives with an alcohol–benzene solvent.[9] Figure 3 also shows the radial variation of BD after extraction with an ethanol–toluene solvent. After extraction, BD showed a gradual increase from pith to bark in all categories. Some BD values of xylem near the pith in the fast and middle categories were considerably decreased by extraction with organic solvent. However, a reduction in BD by extraction was not observed in slow-growing trees. As a result, the mean values of BD after extraction also decreased: 0.50, 0.52, and 0.43 g/cm^3 for fast-, middle-, and slow-growing trees, respectively (Table 2). In addition, a significant difference in BD after extraction was recognized among the growth categories at the 1% level: slow-growing trees showed apparently lower values compared to the fast- and middle-growing trees.

In the present study, the correlation coefficients of BD after extraction were determined for 2, 3, 4, and 5 cm from the pith and 2, 3, 4, and 5 cm from the bark side, respectively. The highest correlation coefficient ($r = 0.672$, 1% level) was obtained between the position of 4 cm from pith and 4 cm from the bark (Table 3), suggesting that the early selection of trees with a high BD by using the BD at 4 cm from the pith is possible for *P. merkusii*.

Compressive strength

The mean values of CS were 29.4, 26.9, and 23.0 MPa for fast-, middle-, and slow-growing trees, respectively (Table 2). The CS in the green condition of *P. merkusii* has been reported to be 26 MPa in trees from Indonesia, 15 MPa in those from Malaysia, and 27 MPa in those from the Philippines.[2,10] The values were similar to those in this study. On the other hand, the mean value of CS in slow-growing trees was lower than that in fast- and middle-growing trees. As a result, a significant difference (analysis of variance, 5%

Table 2. Mean values of wood properties in 15 selected trees

Property	Fast growing ($n = 5$)		Middle growing ($n = 5$)		Slow growing ($n = 5$)		Significance among the category
	Mean	SD	Mean	SD	Mean	SD	
Diameter (cm)	45.4	0.9	35.4	1.3	23.7	2.5	**
Tree height (m)	32.5	2.3	33.6	0.7	21.5	3.1	**
SWV (km/s)	4.51	0.22	4.78	0.26	4.20	0.27	*
BD before extraction (g/cm^3)	0.53	0.07	0.55	0.06	0.44	0.02	**
BD after extraction (g/cm^3)	0.50	0.06	0.52	0.02	0.43	0.03	**
CS (MPa)	29.4	5.0	26.9	1.3	23.0	2.9	*

BD, basic density; CS, compressive strength parallel to grain
* Significant at 5% level; ** significant at 1% level

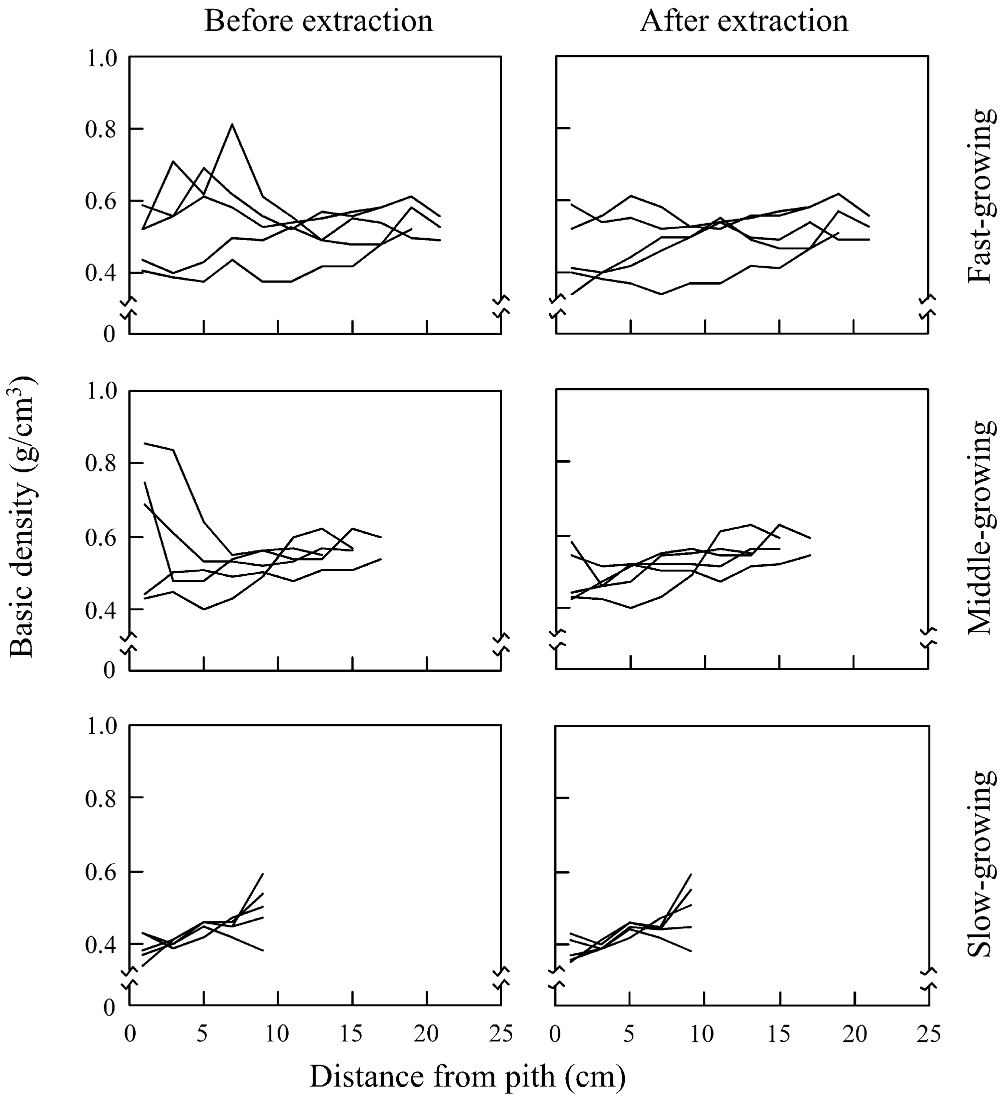

Fig. 3. Radial variation of the basic density before and after extraction with organic solvent

Table 3. Correlation coefficient in basic density after extraction between inner and outer woods

Inner side (position from pith)	Outer side (position from bark side)	Correlation coefficient (n = 15)
2 cm	2 cm	0.461 ns
3 cm	3 cm	0.588*
4 cm	4 cm	0.672**
5 cm	5 cm	0.598*

*Significant at 5% level; **significant at 1% level; ns, not significant

level) was recognized among categories: slow-growing trees showed lower values compared to the fast- and middle-growing trees. These results indicate that the nature of slow growth results in a reduction of CS compared to that of the fast- and middle-growth categories.

The CS gradually increased from pith to bark in all categories (Fig. 4). In a previous report,[4] the CS in *P. densiflora* was found to gradually increase from pith to bark. Machado and Cruz[11] examined the within-tree variation of CS in *P. pinaster*. They reported that the CS increased from a 10% relative distance from pith to bark (RD) to a 50% RD, and a comparable mean CS was obtained for 50% RD and 90% RD. The results obtained in this study were similar to those obtained by other researchers.[4,11]

It is well known that CS is highly correlated with density.[12] Figure 5 shows the relationship between BD and CS in all specimens from the three growth categories. In the present study, a significant, positive correlation coefficient ($r = 0.443$, 1% level) was obtained between BD and CS. The correlation coefficient between BD after extraction and CS increased ($r = 0.787$, 1% level, Fig. 5), indicating that the CS is largely affected by the BD after extraction.

Wood properties with respect to the relative distance from pith to bark

The maturation process of wood properties in softwood species growing in the temperate zone depends on the

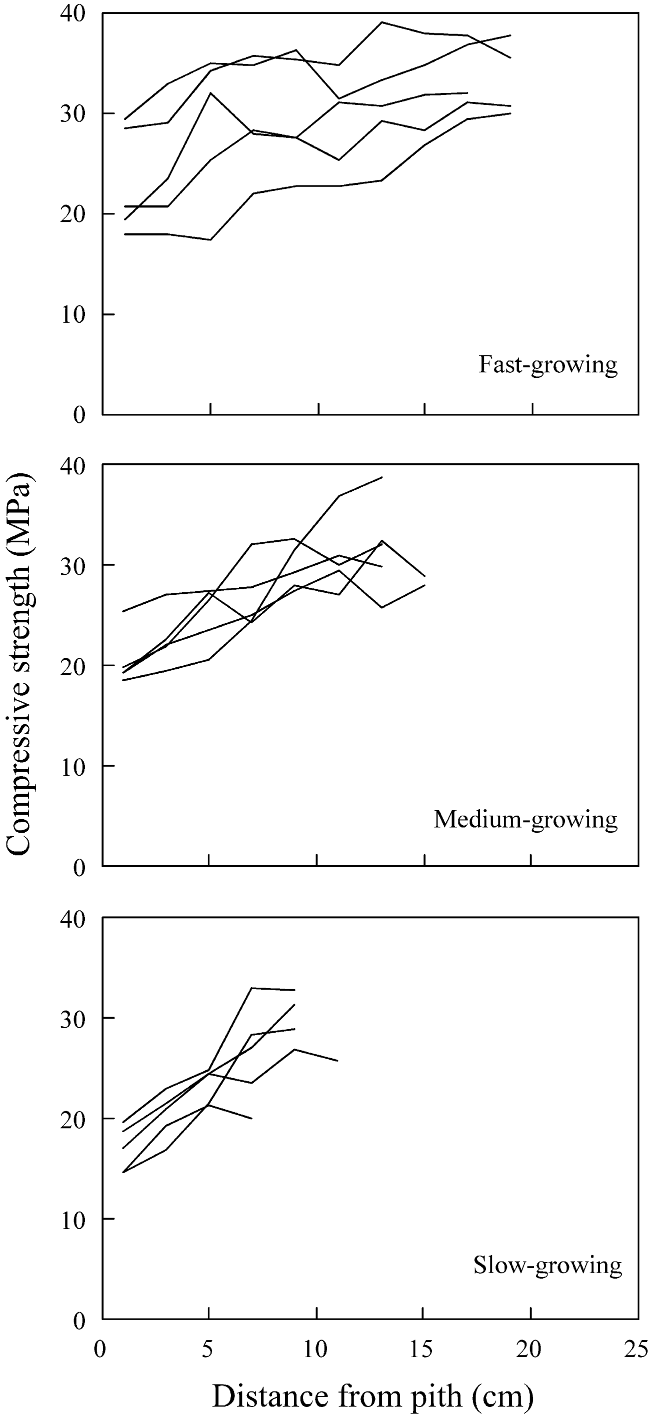

Fig. 4. Radial variation of the compressive strength parallel to the grain

cambial age.[9] Recently, on the other hand, several researchers have reported that the maturation process of the xylem depends on the diameter growth in some tropical hardwood species, such as *Acacia mangium* and *Paraserianthes falcataria*.[13–15] Figure 6 shows variation of the mean values of BD after extraction and CS for each category with respect to the relative distance from pith to bark. In both BD after extraction and CS, the radial profiles in each category showed almost the same pattern. These results suggest that the BD and CS in *P. merkusii* depend on the cambial age. In other words, the boundary between juvenile wood and mature wood may be determined by the cambial age.

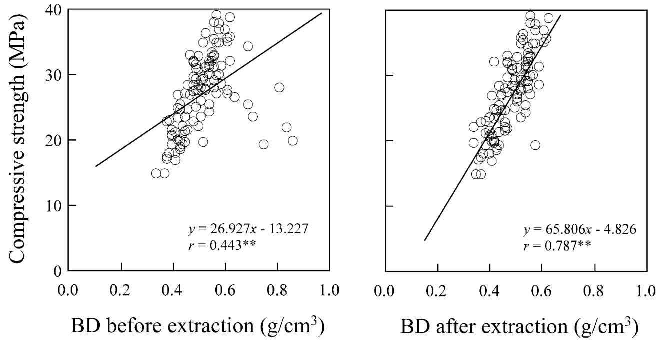

Fig. 5. Relationship between basic density (*BD*) before and after extraction and the compressive strength. *r*, correlation coefficient; **, significant at the 1% level

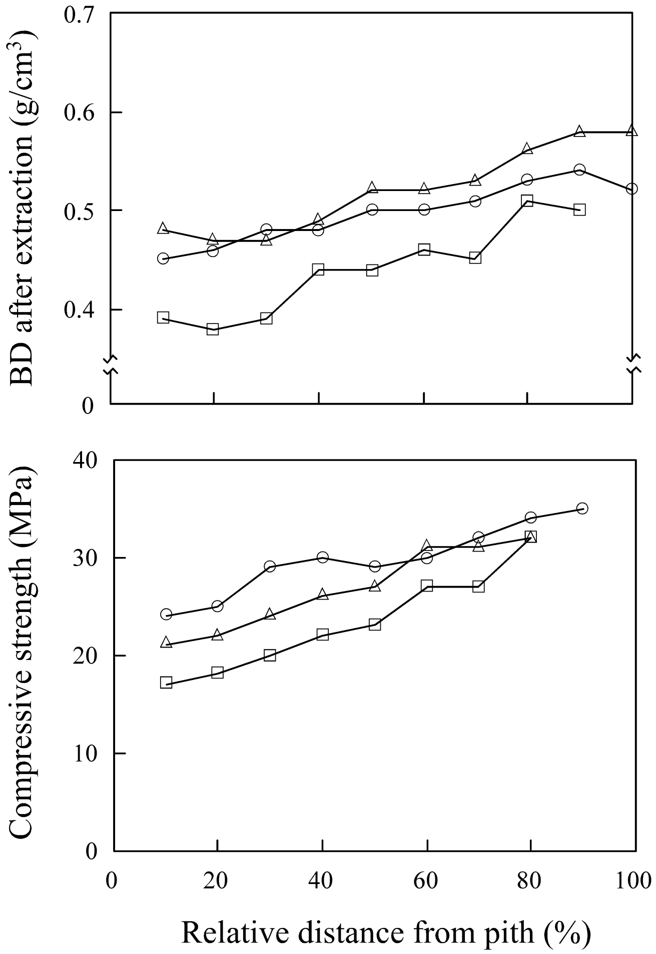

Fig. 6. Radial variation of the basic density (BD) after extraction and compressive strength in regard to the relative distance from the pith. *Circles*, fast-growing trees; *triangles*, middle-growing trees; *squares*, slow-growing trees. Data are the mean values of five trees in each category. Values in regard to the relative distance from pith were determined by the method described in Chowdhury et al.[5]

However, the maturation process of the xylem is usually determined by the radial profile of cell length, such as in tracheid and wood fiber.[13–15] Thus, further research is needed to clarify the maturation process in *P. merkusii*.

Conclusions

The following results were obtained in the present study:

1. No significant correlation coefficient was found between the stem diameter and SWV of standing trees.
2. BD in slow-growing trees was apparently lower than BD in fast- and middle-growing trees. BD of xylem near the pith in fast- and middle-growing trees was reduced by extraction with organic solvent. As a result, BD after extraction gradually increased from the pith to bark in all growth categories.
3. A significant correlation in BD was recognized between the positions of 4 cm from the pith and 4 cm from the bark side, indicating that early selection of trees with high BD is possible for this species.
4. CS increased from pith to bark in the three growth categories. In addition, a significant difference was found among the three categories. Moreover, CS was significantly correlated with BD after extraction.
5. The results of the radial variation of BD and CS with regard to the relative distance from pith to bark suggest that they depend on the cambial age.

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References

1. Ogata K, Fujii T, Abe H, Bass P (2008) Identification of the timbers of Southeast Asia and the Western Pacific. Kaiseisha, Otsu
2. Soerianegara I, Lemmens RHMJ (1994) Plant resources of South-East Asia 5 (1) Timber trees: Major commercial timbers. Prosea, Bogor
3. Ishiguri F, Wahyudi I, Takeuchi M, Takashima Y, Iizuka K, Yokota S, Yoshizawa N (2011) Wood properties of *Pericopsis mooniana* grown in a plantation in Indonesia. J Wood Sci 57:241–246
4. Matsumoto K, Ishiguri F, Iizuka K, Yokota S, Yoshizawa N (2009) Evaluation of bending and compression strength of wood using a Fractometer (in Japanese). Wood Ind 63:358–363
5. Chowdhury MQ, Ishiguri F, Iizuka K, Takashima Y, Matsumoto K, Hiraiwa T, Ishido M, Sampe H, Yokota S, Yoshizawa N (2009) Radial variations of wood properties in *Casuarina equisetifolia* growing in Bangladesh. J Wood Sci 55:139–143
6. Grabianowski M, Manley B, Walker J (2004) Impact of stocking and exposure on outerwood acoustic properties of *Pinus radiata* in Eyrewell forest. NZ J Forest 49(2):13–17
7. Chauhan SS, Walker JCF (2006) Variations in acoustic velocity and density with age, and their interrelationships in radiata pine. Forest Ecol Manag 229:388–394
8. Ikeda K, Arima T (2000) Quality evaluation of standing trees by a stress-wave propagation method and its application II. Evaluation of sugi stands and application to production of sugi (*Cryptomeria japonica* D. Don) structural square sawn lumber (in Japanese). Mokuzai Gakkaishi 46:189–196
9. Zobel BJ, van Buijtenen JP (1989) Wood variation, its causes and control. Springer-Verlag, Berlin, Heidelberg, New York
10. Chudnoff M (1980) Tropical timbers of the world. US Department of Agriculture, Forest Service, Forest Products Laboratory, Washington, DC
11. Machado JS, Cruz HP (2005) Within-stem variation of maritime pine timber mechanical properties. Holz als Roh- und Werkstoff 63:154–159
12. Kollman FFP, Côté WA (1984) Principles of wood science and technology, vol 1: solid wood. Springer, Berlin, Heidelberg, New York
13. Honjo K, Furukawa I, Sahri MH (2005) Radial variation of fiber length increment in *Acacia mangium*. IAWA J 26:339–352
14. Kojima M, Yamamoto H, Yoshida M, Ojio Y, Okumura K (2009) Maturation property of fast-growing hardwood plantation species: A view of fiber length. Forest Ecol Manag 257:15–22
15. Kojima M, Yamamoto H, Okumura K, Ojio Y, Yoshida M, Okuyama T, Ona T, Matsune K, Nakamura K, Ide Y, Marsoem SN, Sahri MH, Hadi YS (2009) Effect of the lateral growth rate on wood properties in fast-growing hardwood species. J Wood Sci 55:417–424