AMONG-CLONE VARIATIONS OF ANATOMICAL CHARACTERISTICS AND WOOD PROPERTIES IN *TECTONA GRANDIS* PLANTED IN INDONESIA

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Abstract. Anatomical characteristics (vessel diameter [VD], fiber wall thickness [FWT], fiber diameter [FD], vessel element length [VEL], and fiber length [FL]) and wood properties (basic density [BD] and compressive strength parallel to grain [CS] in the green condition) were determined for 27 12-yr-old teak trees planted in Java Island, Indonesia. The mean values of VD, FWT, FD, VEL, FL, BD, and CS were 188 μm, 2.78 μm, 23.4 μm, 284 μm, 1.42 mm, 510 kg/m^3, and 37.5 MPa, respectively. Significant differences in VEL, BD, and CS occurred among the nine clones. Moderate to high values of repeatability were obtained for FD, VEL, BD, and CS, indicating that these characteristics are genetically controlled. Radial variation of FL with respect to relative distance showed almost the same pattern for two different radial growth rates (faster and slower) at the same age, suggesting that xylem maturation in teak trees depends on cambial age rather than stem diameter.

Keywords: *Tectona grandis*, clones, anatomical characteristics, wood properties, repeatability.

INTRODUCTION

Teak (*Tectona grandis* L.f.) is an important commercial plantation species, and demand for teak wood is increasing in Indonesia. However, the total wood production of this species is decreasing because teak wood resources have declined and productivity of the plantations is low. Tree breeding programs for teak were started by the Indonesian State Forest Enterprise in 1981 to obtain genetically improved seed for increasing productivity of teak plantations. Since the beginning of 1990, seeds from clonal seed orchards have also been available, although the amount of seed is still limited (Suseno 2000). As part of these programs, 200 superior parent teak trees were selected from several plantations in East and Central Java, Indonesia. From these, 65 clones were selected for progeny testing. Several progeny test sites were established in February 1999 at four locations (Cepu, Ngawi, Bojonegoro, and Ciamis) on Java Island (Na'iem 2000). Stem diameter and tree height at 16 mo were found to be significantly different among clones and across sites (Na'iem 2000). In Hidayati et al (2013), stem diameter, tree height, bole volume, stress-wave velocity, and Pilodyn penetration were investigated for 15 12-yr-old teak clones planted at 2 sites (Cepu, Central Java, and Ciamis, West Java). Among-clone differences were found among the 15 clones in all characteristics, whereas differences between the 2 sites were found only in growth characteristics (stem diameter, tree height, and bole volume). Based on these results, we concluded that the wood properties of teak trees can be improved by tree breeding programs (Hidayati et al 2013).

Wood density is affected by several wood structures, including cell size, cell wall thickness, and some other factors (Zobel and van Buijtenen 1989). Variations in wood structure have a significant effect on wood quality. In general, basic density is an important factor affecting wood properties (Zobel and van Buijtenen 1989). Compressive strength is also one of the important mechanical properties of solid lumber (Thulasidas and Bhat 2012). However, information on anatomical characteristics and wood properties continues to be limited and requires elucidation for teak breeding programs in Indonesia.

To use faster growing trees, it is important to know if xylem maturation depends on cambium age or tree diameter and when the maturation process occurs. Understanding the maturation process is crucial not only for forest management, but also for avoiding problems for manufacturers and consumers (Kojima et al 2009). Xylem maturation of some fast-growing species, such as *Acacia mangium* and *Paraserianthes falcataria*, depends on diameter growth (Honjo et al 2005; Kojima et al 2009; Makino et al 2012). In contrast, xylem maturation of *Eucalyptus* spp. and *Shorea acuminatissima* depends on cambial age (Kojima et al 2009; Ishiguri et al 2012). In teak, Bhat et al (2001) reported that maturation begins approximately at 15-25 yr of age, depending on the property, growth rate, individuality, and plantation site. However, the mechanism of xylem maturation in teak trees remains unclear.

In this study, anatomical characteristics (vessel diameter [VD], fiber wall thickness [FWT], fiber diameter [FD], vessel element length [VEL], and fiber length [FL]) and wood properties (basic density [BD] and compressive strength parallel to grain [CS] in the green condition) were determined for 9 12-yr-old teak clones planted in Java Island, Indonesia. Based on the results, we discussed the variation among clones, repeatability, radial variations of the anatomical characteristics and wood properties, and relationships among the properties.

MATERIALS AND METHODS

Materials

A total of 27 12-yr-old teak trees representing nine clones (clones A–I) with 2-5 replications for each clone were used in this study (Table 1). The clonal test sites were located in Cepu (latitude 7°01′ S, longitude 111°32′ E) and Ciamis (latitude 7°19′ S, longitude 108°32′ E), Indonesia. These clonal test plantations were established in February 1999. The trees were initially planted at a spacing of 3 × 3 m. After planting, no fertilizer was applied. In 2007, the trees were thinned by 50%. Environmental conditions at the two clonal test sites are described in Table 2 (Hidayati et al 2013).

Table 1. Statistical values of stem diameter and tree height of sample trees.[a]

Clone code	Site	Number of trees	D (cm)		TH (m)	
			Mean	SD	Mean	SD
A	Ciamis	2	21.3	3.6	17.0	0.0
B	Cepu	3	17.1	1.0	14.8	1.9
B	Ciamis	2	23.1	0.4	18.0	1.4
C	Ciamis	3	23.2	2.0	15.7	2.1
D	Ciamis	3	19.6	2.4	14.8	4.1
E	Ciamis	3	21.7	1.0	17.0	3.3
F	Cepu	3	17.6	1.6	12.0	3.6
G	Cepu	2	17.1	2.0	12.8	3.2
H	Cepu	3	17.2	1.0	14.7	0.8
I	Cepu	3	17.3	1.8	14.0	2.6
Mean/total		27	19.5	2.6	15.1	1.9

[a] SD, standard deviation; D, stem diameter; TH, tree height.

Table 2. Environmental conditions at the two clonal test sites (Hidayati et al 2013).

	Cepu	Ciamis
Province	Central Java	West Java
Latitude (S)	7°01′	7°19′
Longitude (E)	111°32′	108°32′
Altitude (m)	50	300
Precipitation (mm/yr)	1436	2740
Mean temperature (°C)	27.5	25.0
Soil type	Vertisol	Inceptisol
Topography	Flat	Flat

For determining anatomical characteristics and wood properties, core samples (5 mm in diameter) from pith to bark were collected using a borer (Haglöf, Langsele, Sweden) at 1.3 m above ground level. Three core samples were collected from each tree at the circumferential position. With the core samples, anatomical characteristics (VD, FWT, FD, VEL, and FL) and wood properties (BD and CS) were determined from pith to bark. It is known that false rings sometimes occur in teak because of environmental factors (Priya and Bhat 1998; Palakit et al 2012). Thus, the core samples were cut at 10-mm intervals from pith to bark for determining radial variations of the anatomical characteristics and wood properties. For determining CS, samples were cut into small pieces at 5-mm intervals from pith to bark.

Anatomical Characteristics

Transverse sections (20 μm thick) were obtained from each 10-mm segment with a sliding microtome. Sections were stained with safranin, dehydrated, and mounted in biolet. Digital images of the transverse sections were captured into a personal computer and analyzed with ImageJ software (National Institutes of Health, Bethesda, MD). The tangential and radial diameters were measured for 30 vessels and 50 wood fibers in each 10-mm segment, and mean values were calculated. The double wall thicknesses of 50 wood fiber cells were measured, and one-half of the double-wall thickness was defined as FWT. Small strip specimens were macerated with Schulze's solution for measuring VEL and FL.

A total of 30 vessel elements and 50 wood fibers were measured using a microprojector (Nikon [Tokyo, Japan], V-12) and a digital caliper (Mitutoyo [Kanagawa, Japan], CD-15CP). All anatomical characteristics were measured except for pore and terminal zones of the growth ring.

Wood Properties

The green volume of each segment was measured using the water displacement method, and the oven-dried weight was determined by drying the segment to a constant weight at 105°C in a laboratory oven (WFO-450ND; EYELA, Tokyo, Japan). BD was calculated by dividing the oven-dried weight by the green volume. CS in the green condition was measured using a core sample testing machine (Fractometer II; IML, Moultonborough, NH) in accordance with the method described by Matsumoto et al (2010). A specimen was placed in the testing machine, and a load was applied in the longitudinal direction. The CS value indicated by the testing machine was recorded for each specimen. The mean value of CS at 10-mm intervals was calculated before analysis of radial variation.

Statistical Analysis

Table 3 shows the stem diameter, anatomical characteristics, and wood properties of clone B from the two clonal test sites. In Hidayati et al (2013), a significant difference between two sites was recognized only in diameter, a growth characteristic (Table 3). Therefore, data from the two sites were combined to analyze among-clone variation of the anatomical characteristics and wood properties. Analysis of variance (ANOVA) was applied to evaluate differences among clones with respect to the anatomical characteristics and wood properties. The following model of ANOVA was used for each anatomical characteristic and wood property:

$$Y_{ij} = \mu + S_i + C_j + \varepsilon_{ij} \quad (1)$$

where Y_{ij} is the parameter of the jth clone in the ith replication, μ is the overall mean, S_i is the site effect of the ith replication, C_j is the genetic effect of the jth clone, and ε_{ij} is the error in Y_{ij}. Clonal repeatability of the anatomical characteristics and wood properties was estimated using the following formula proposed by Falconer (1989) for assessing the magnitude of genetic effects:

$$H^2 = {\sigma_c}^2 / \left[{\sigma_c}^2 + {\sigma_e}^2\right] \quad (2)$$

where H^2 denotes clonal repeatability/broad-sense heritability, ${\sigma_c}^2$ denotes the variance component for clone, and ${\sigma_e}^2$ denotes the variance component of environmental factors.

Table 3. Comparison of mean values of anatomical characteristics and wood properties of clone B between the two clonal test sites.[a]

Character	Cepu (n = 3) Mean	SD	Ciamis (n = 2) Mean	SD	Significant between two sites
D (cm)	17.1	1.0	23.1	0.4	**
VD (μm)	182	10	196	0.3	NS
FWT (μm)	2.78	0.14	2.92	0.01	NS
FD (μm)	23.3	1.4	23.3	0.9	NS
VEL (μm)	289	2	300	6	NS
FL (mm)	1.41	0.1	1.52	0.01	NS
BD (kg/m^3)	510	30	520	20	NS
CS (MPa)	39.1	2.9	37.9	0.2	NS

[a] SD, standard deviation; D, stem diameter; VD, vessel diameter; FWT, fiber wall thickness; FD, fiber diameter; VEL, vessel element length; FL, fiber length; BD, basic density; CS, compressive strength parallel to grain.

** Significance at 1% level; NS, no significance.

Evaluation of Xylem Maturation Process

Radial variation of FL with respect to relative distance from the pith was calculated for evaluating the xylem maturation process. The calculation method proposed by Chowdhury et al (2009b) was used. A total of 10 trees of the same age with different radial growth rates was selected (5 trees with faster growth and 5 trees with slower growth).

RESULTS AND DISCUSSIONS

Anatomical Characteristics

The highest values of VD, FWT, FD, VEL, and FL were 196 μm, 2.89 μm, 24.5 μm, 293 μm, and 1.48 mm for clones H, A, I, B, and C, respectively. The lowest values of VD, FWT, FD, VEL,

Table 4. Statistical values of anatomical characteristics of each clone.[a]

Clone code	Number of trees	VD (μm)		FWT (μm)		FD (μm)		VEL (μm)		FL (mm)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
A	2	175	17	2.89	0.16	22.8	0.2	268	1	1.42	0.09
B	5	188	10	2.84	0.12	23.3	1.1	293	7	1.46	0.09
C	3	190	9	2.77	0.15	23.4	0.5	290	7	1.48	0.02
D	3	189	7	2.58	0.20	23.1	0.2	272	10	1.38	0.10
E	3	195	10	2.77	0.08	23.8	0.5	283	13	1.39	0.07
F	3	188	11	2.82	0.17	23.7	0.8	284	13	1.43	0.05
G	2	188	5	2.85	0.19	23.0	0.6	282	1	1.38	0.13
H	3	196	14	2.69	0.22	23.1	0.3	291	10	1.41	0.04
I	3	187	6	2.85	0.27	24.5	0.5	289	7	1.44	0.04
Mean/total	27	188	6	2.78	0.10	23.4	0.5	284	9	1.42	0.04
Significance among clones		NS		NS		NS		*		NS	
σ_c^2		—		—		0.125		46.42		—	
σ_e^2		104.0		0.031		0.452		84.07		0.005	
H^2		—		—		0.22		0.36		—	

[a] SD, standard deviation; VD, vessel diameter; FWT, fiber wall thickness; FD, fiber diameter; VEL, vessel element length; FL, fiber length.
* Significance at 5% level; NS, no significance; σ_c^2, variance component of clone; σ_e^2, variance component of environment; H^2, clonal repeatability/broad-sense.

and FL were 175 μm, 2.58 μm, 22.8 μm, 268 μm, and 1.38 mm for clones A, D, A, A, and D and G, respectively (Table 4). In some hardwood species such as *Eucalyptus camaldulensis,* acacia hybrid, and *A. mangium*, no significant differences were found in VD, FWT, FD, VEL, and FL among clones and provenances (Veenin et al 2005; Kim et al 2008; Nugroho et al 2012). In contrast, in *Populus deltoides*, significant differences among clones were recognized in VD, FWT, FD, VEL, and FL (Pande 2011; Pande and Dhiman 2011). In this study, a significant difference was found only in VEL. Table 4 presents the results of ANOVA and repeatability of the anatomical characteristics for the nine clones. In this study, moderate values of repeatability were obtained for VEL and FD (Table 4). However, repeatability values could not be calculated for the other characteristics.

Wood Properties

Table 5 shows the mean values of wood properties in the nine clones. The highest values of BD and CS in the green condition were 580 kg/m^3 and 42.9 MPa, respectively, for clone A, and the lowest values were 480 kg/m^3 and 33.7 MPa, respectively, for clone D. Furthermore, BD and CS were significantly different among clones (Table 5). Indira and Bhat (1998) reported a significant difference in BD among 18 14-yr-old teak clones planted in India. Nocetti et al (2011) found that wood density significantly differed among 13 provenances of teak planted in Ghana. Significant differences in wood density among clones were also found in some hardwood species, such as acacia hybrid and *P. deltoides* (Kim et al 2008; Pande and Dhiman 2011). CS was significantly different between two provenances of teak trees (Bhat and Priya 2004). Furthermore,

Table 5. Statistical values of wood properties of each clone.[a]

Clone code	Number of trees	BD (kg/m^3)		CS (MPa)	
		Mean	SD	Mean	SD
A	2	580	20	42.9	0.0
B	5	510	20	38.6	2.2
C	3	500	30	35.7	3.0
D	3	480	30	33.7	0.3
E	3	510	30	34.6	2.6
F	3	510	30	39.9	1.3
G	2	530	10	39.2	1.3
H	3	490	30	34.0	1.8
I	3	520	00	38.6	1.4
Mean/total	27	510	30	37.5	3.1
Significance among clones		*		**	
σ_c^2		0.0004		6.881	
σ_e^2		0.0007		4.510	
H^2		0.39		0.60	

[a] SD, standard deviation; BD, basic density; CS, compressive strength parallel to grain at green condition.
** Significance at 1% level; * significance at 5% level; σ_c^2, variance component of clone; σ_e^2, variance component of environment; H^2, clonal repeatability/broad-sense.

Table 6. Correlation coefficients between measured characteristics.[a]

Character	VD	FWT	FD	VEL	FL	BD	CS
VD							
FWT	−0.071 NS						
FD	0.276 NS	0.035 NS					
VEL	0.436*	−0.041 NS	0.342 NS				
FL	0.172 NS	0.344 NS	−0.001 NS	0.283NS			
BD	−0.353 NS	0.535**	0.139 NS	−0.362 NS	0.177 NS		
CS	−0.540**	0.574**	−0.054NS	−0.164 NS	0.122 NS	0.719**	

[a] VD, vessel diameter; FWT, fiber wall thickness; FD, fiber diameter; VEL, vessel element length; FL, fiber length; BD, basic density; CS, compressive strength parallel to grain.

** Significance at 1% level; * significance at 5% level; NS, no significance.

moderate values of repeatability of BD and specific gravity were obtained in other hardwood species such as *Acacia auriculiformis* and *P. deltoides* (Hai et al 2010; Pande and Dhiman 2011). However, studies of heritability in compressive strength are limited. With respect to other mechanical properties, Moya and Marín (2011) reported that the repeatability of dynamic modulus of elasticity was 0.34 in 10-yr-old teak trees planted in Costa Rica. In this study, significant differences were found among clones, and repeatability of BD and CS showed moderate to high values (Table 5), indicating that BD and CS are genetically controlled in teak. Thus, we inferred that BD and CS are substantial properties for improving wood quality in teak tree breeding programs.

Relationships among Properties

Table 6 shows the correlation coefficients among the measured characteristics. A significant correlation among the anatomical characteristics was found only between VD and VEL. Conversely, some significant correlations were found between the anatomical characteristics and wood properties. Furthermore, a significant positive correlation was found between BD and FWT (Table 6). In 35-yr-old teak trees planted in India, air-dry density was positively and significantly correlated with double-wall thickness, and CS was also correlated with air-dry density and double-wall thickness (Thulasidas and Bhat 2012). Similar results have been reported for other hardwood species (Ishiguri et al 2009; Chowdhury et al 2009a, 2009b, 2012; Matsumoto et al 2010; Makino et al 2012). These results indicate that FWT was strongly correlated with BD in teak.

Radial Variations of Measured Characteristics

Radial variations of VD and FWT gradually increased from pith to bark (Fig 1). FD slightly increased near the pith and then became constant outward (Fig 1). Bhat et al (2001) reported that VD increased during the juvenile phase and then stabilized at approximately 20 yr. In other hardwood species with long rotations, FWT increased from pith to bark, whereas FD was almost constant from pith to bark in *S. acuminatissima* (Ishiguri et al 2012). In this study, radial variations of VD, FWT, and FD (Fig 1) were almost similar to those reported in previous studies (Bhat et al 2001; Ishiguri et al 2012). Radial variations of VEL and FL showed a gradual increase from pith to bark (Fig 2). In teak trees, FL increased up to 15-20 yr and then became constant outward (Bhat et al 2001). Furthermore, radial variation of BD also showed a gradual increase from pith to bark (Fig 3). In contrast, Bhat et al (2001) reported that BD varied relatively little from pith to bark. They also reported that CS varied little and slightly increased from pith up to 20 cm (the juvenile wood area). In this study, radial variation of CS agreed with that reported in a previous study (Bhat et al

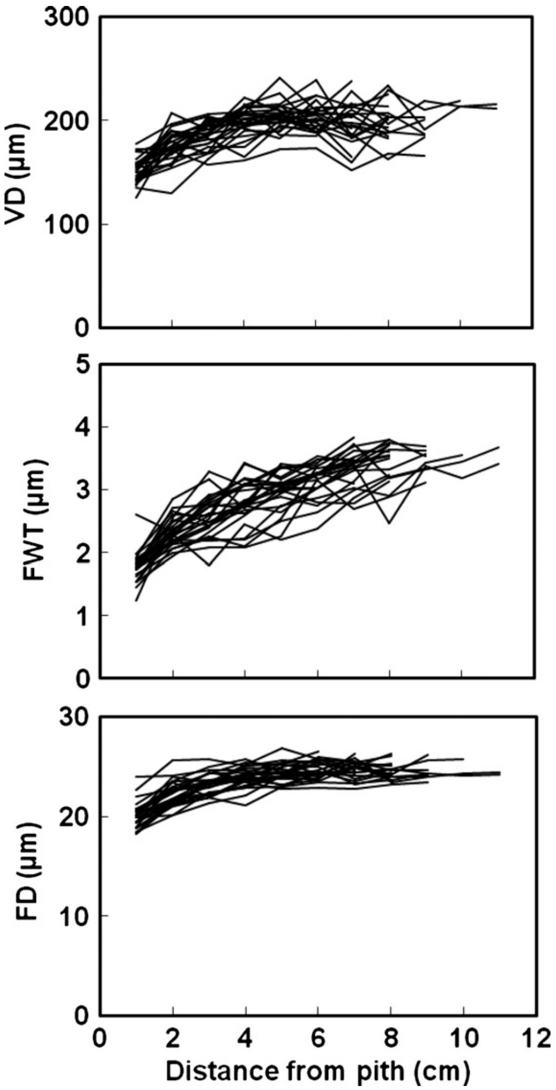

Figure 1. Radial variations of vessel diameter (VD), fiber wall thickness (FWT), and fiber diameter (FD) from pith to bark in 27 trees from nine clones.

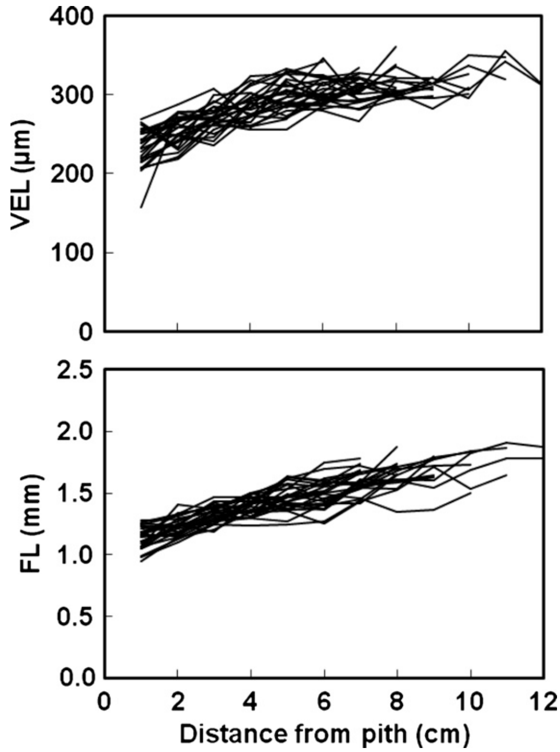

Figure 2. Radial variations of vessel element length (VEL) and fiber length (FL) from pith to bark in 27 trees from nine clones.

2001). Thus, trends of radial variations of the anatomical characteristics and wood properties were similar for all clones.

Radial variation of FL determined by relative distance from the pith was also examined. Figure 4 shows radial variation of FL in the 10 selected trees (5 with faster radial growth rate and 5 with slower radial growth rate). The radial profile in relation to relative distance from the pith showed almost the same pattern for the two radial growth rate categories (Fig 4), suggesting that xylem maturation in teak trees depends on cambial age rather than stem diameter. It has been reported that xylem maturation in some fast-growing species, such as *A. mangium* and *P. falcataria*, depends on diameter growth (Honjo et al 2005; Kojima et al 2009; Makino et al 2012). In contrast, xylem maturation in *Eucalyptus* spp. and *S. acuminatissima* was reported to depend on cambial age (Kojima et al 2009; Ishiguri et al 2012). Bhat et al (2001) reported that the maturity of teak begins at approximately 15-25 yr. Although the tree age used in this study was relatively younger, our results suggesting that xylem maturation in teak depends on cambial age are consistent with those obtained by Bhat et al (2001). Therefore, we conclude that at 12 yr after planting, intensive silvicultural practices

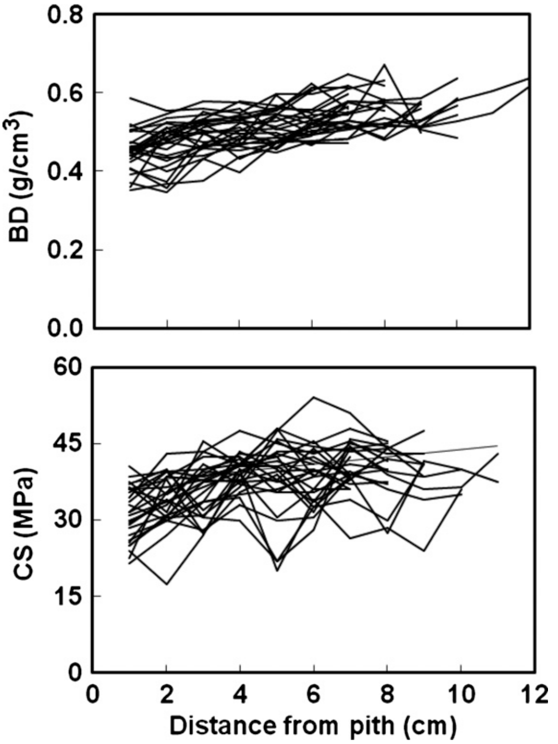

Figure 3. Radial variations of basic density (BD) and compressive strength parallel to grain (CS) in the green condition from pith to bark in 27 trees from nine clones.

should be applied to produce as much mature wood as possible in teak trees.

CONCLUSIONS

Anatomical characteristics and wood properties were investigated for 27 trees from nine teak clones planted in Indonesia. Clone A showed the lowest values of VD, FD, and VEL and the highest values of FWT, BD, and CS. The mean values of VD, FWT, FD, VEL, FL, BD, and CS were 188 μm, 2.78 μm, 23.4 μm, 284 μm, 1.42 mm, 510 kg/m^3, and 37.5 MPa, respectively. Significant differences among the nine clones were found in VEL, BD, and CS. Moderate to high values of repeatability were obtained for FD, VEL, BD, and CS, indicating that these characteristics are genetically controlled. Radial variation of FL with respect to relative distance from the pith showed almost the same pattern for the

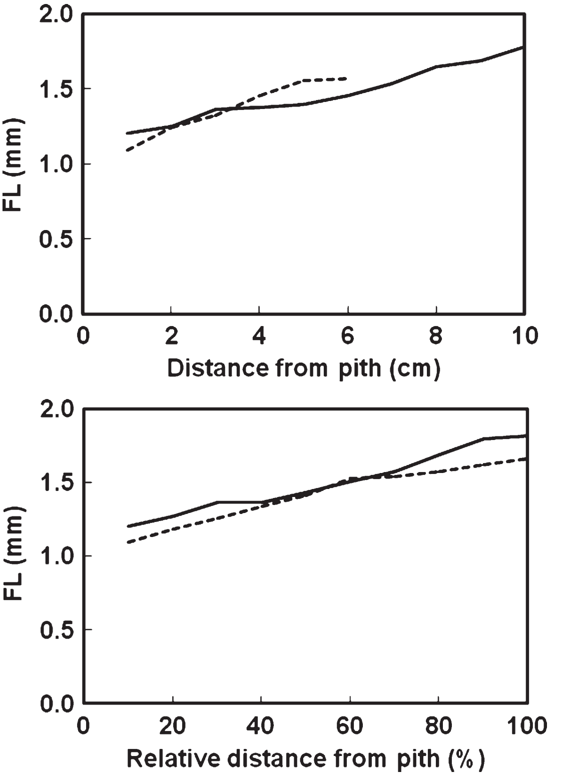

Figure 4. Radial variations of fiber length (FL) with respect to distance from the pith and relative distance from the pith in the 10 selected trees with different radial growth rates. Solid line indicates mean value of five trees with faster radial growth rate; dotted line indicates mean value of five trees with slower radial growth rate.

two radial growth rate categories, suggesting that xylem maturation depends on cambial age rather than stem diameter in teak trees. Therefore, we conclude that 12 yr after planting, intensive silvicultural practices should be applied to produce as much mature wood as possible in teak trees.

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