ORIGINAL ARTICLE

Wood properties and simulated modulus of elasticity of glulam in three fast-growing tree species grown in community forests in Yogyakarta, Java Island, Indonesia

Agus Ngadianto^{1,2,3}, Futoshi Ishiguri^{1*}, Ikumi Nezu¹, Yusuke Takahashi¹, Jun Tanabe⁴, Fanny Hidayati⁵, Denny Irawati⁵, Jyunichi Ohshima¹ and Shinso Yokota¹

¹ School of Agriculture, Utsunomiya University, Utsunomiya 321-8505, Japan

² United Graduate School of Agricultural Science, Tokyo University of Agriculture and Technology, Fuchu, Tokyo 183-8509, Japan

³ Vocational College, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia

⁴ Faculty of Education, Chiba University, Chiba 263-8522, Japan

⁵ Faculty of Forestry, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia

* Corresponding author: ishiguri@cc.utsunomiya-u.ac.jp

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ABSTRACT Community forests in Indonesia are important suppliers of wood resources for the wood industry. In the present study, stress-wave velocity of stems, log characteristics (taper, green density, and dynamic Young's modulus), and wood properties (basic density, compressive strength parallel to grain, modulus of elasticity [MOE], and modulus of rupture [MOR]) were investigated for three fast-growing tree species grown in community forests in Indonesia: *Acacia mangium* Willd., *Maesopsis eminii* Engl., and *Melia azedarach* L. Based on the bending properties, the MOE values of laminae (30 × 150 mm in cross-section) and glulam (six layers, 90 × 150 mm in cross-section) were simulated. The mean values of simulated MOE in the laminae were 8.93, 6.82, and 8.63 GPa for *A. mangium*, *M. eminii*, and *M. azedarach*, respectively. When the laminae from a species were randomly laminated, the simulated MOE values of glulam were 8.94, 6.82, and 8.66 GPa for *A. mangium*, *M. eminii*, and *M. azedarach*, respectively. When laminae with a high, medium, and low MOE were laminated at outer, middle, and inner layers of glulam, respectively, the simulated MOE values of glulam increased by about 5 % to 15 % compared to the values of a randomly laminated one. It is concluded that glulam with a high MOE can be produced from fast-growing tree species grown in community forests in Indonesia.

Key words: community forest, glulam, wood properties, radial variation

INTRODUCTION

In Indonesia, increasing wood demands are a reason for forest loss and degradation (Tsujino et al. 2016). It is important to utilize the community forest combined with agroforestry for preventing forest loss and degradation because the community forests managed by local people can sustainably supply both food and wood resources (Ota 2011; Maryudi et al. 2017). In fact, large amounts of wood resources are supplied to the wood industry in Indonesia by community forests (Maryudi et al. 2017). In Indonesian community forests, local people plant commercial plantation species, such as *Tectona grandis* L.f. and *Acacia mangium* Willd., as well as other fast-growing tree species, such as *Falcataria moluccana* Miq. (syn. *Paraserianthes falcataria* L.) and *Neolamarckia cadamba* (Roxb.) Bosser (syn. *Anthocephalus cadamba* Miq.) (Siregar et al. 2007;

Ota 2011; Seo et al. 2015).

Wood properties have been investigated for several fast-growing tree species planted in Indonesia, such as *F. moluccana* (Ishiguri et al. 2007; Fajriani et al. 2013), *Gmelina arborea* (Kim et al. 2012; Hidayati et al. 2017), and *A. cadamba* (Fajriani et al. 2013; Seo et al. 2015; Pertiwi et al. 2017). However, available information is limited on the wood properties of other fast-growing tree species grown in the community forest in Indonesia. In addition, most of the fast-growing tree species were originally intended to be used for raw materials in pulp and paper production (Alamsyah et al. 2007), suggesting that strength properties and dimension stability are not required for the wood of fast-growing tree species. However, the common fast-growing tree species are also widely used for solid wood products and wood-based materials (Tenorio et al. 2011). Thus, even in fast-growing tree species, wood properties,

including strength properties and dimension stability, should be considered before the wood is utilized for solid wood products and wood-based materials.

Glulam is a wood-based material. It is an engineered stress-rated product consisting of two or more layers of lamina in which the grain of all layers is oriented parallel to the length of the lamina (Kretschmann and Hernandez 2010). Kretschmann and Hernandez (2010) reported that a large quantity of lower grade lamina could be used within the low stressed laminations of a beam, placing the highest grades in the highly stressed laminations near the top and bottom and the lower grade around the neutral axis. Thus, trial productions or simulations of glulam with a higher modulus of elasticity (MOE) and modulus of rupture (MOR) have been conducted using different grades of laminae (Hayashi 1989; Ohno et al. 2010). However, basic information on wood properties for glulam production is still limited for the wood of fast-growing tropical tree species.

The aim of this study was to produce glulam with high strength properties using wood from fast-growing tree species grown in community forests in Indonesia. With this aim, we targeted three species abundantly found in community forests in Yogyakarta, Java island, Indonesia: *A. mangium*, *M. eminii*, and *M. azedarach*. Basic information about the growth characteristics and the within-tree variations of wood properties were investigated for these species. Based on our results, the MOE of glulam made of laminae from single species was simulated to provide information on wider utilizations of wood from fast-growing tree species grown in community forests.

MATERIALS AND METHODS

Experimental stands

Three fast-growing tree species were used in the present study: *Acacia mangium* Willd., *Maesopsis eminii* Engl., and *Melia azedarach* L. Tree age in *A. mangium*, *M. eminii*, and *M. azedarach* was 7, 7, and 13 years old, respectively. A total of nine trees (three trees of each species) were selected from community forests located in Cangkringan, Sleman, Yogyakarta, Indonesia (7°37' S, 110°27' E). The forests were established by naturally generated *M. eminii* and *M. azedarach* seedlings. For *A. mangium*, seedlings were prepared from seeds provided by the nurseries of Watershed Management and Protected Forest, Serayu Opak Progo, Yogyakarta, Indonesia. No silvicultural treatments, such as thinning, pruning, or fertilizing, were applied in the forests. The growth

characteristics (stem diameter, tree height, and stem volume) of sample trees are listed in Table 1.

Stress-wave velocity and log characteristics

Before the trees were cut down, the stress-wave velocity of stems was measured using a handheld stress-wave timer (Fakopp microsecond timer; Fakopp Enterprise) according to the methods described in our previous report (Ishiguri et al. 2007).

After cutting down the trees, 2 m long logs were obtained from 1.3 m above the ground until the top diameter of each log became less than 11 cm (Fig. 1A). Four to five logs were obtained from each tree. A total of 14, 13, and 15 logs were obtained from *A. mangium*, *M. eminii*, and *M. azedarach*, respectively. After obtaining the logs, the diameter (including bark) of both ends, length, and weight of the logs were measured using diameter tape, a tape meter, and a portable electric balance, respectively.

To determine the stem volume, the volume of each log was calculated using the length and mean values of the diameter at both ends (Fig. 1B). In the present study, the stem volume was regarded as the sum of the log volume from 1.3 m above the ground until the top diameter of each log became less than 11 cm in each tree.

Taper in each log was also calculated by dividing the difference in diameter of the butt and top ends of a log by length of a log. The mean value of logs obtained from a tree was regarded as the taper of the tree.

The dynamic Young's modulus of the logs (DMOE) was determined using the tapping method (Sobue 1986). The green density of logs was determined by dividing green weight by log volume. One end of the log was hit with a small hammer, and the first resonance frequency was obtained using a handheld fast Fourier transform analyzer (AD-3527, A&D) with an accelerometer (PV-85, Rion) set on the opposite end of the log. The DMOE was calculated from the following equation:

$$\text{DMOE (GPa)} = (2Lf)^2 \rho \cdot 10^{-3} \quad (1)$$

where ρ (kg m⁻³) is the density of the log at testing, L (m) is the length of the log, and f (kHz) is the first resonance frequency of the longitudinal vibration.

Wood properties

Figure 1 shows the methods used for sample preparations. Basic density was measured on 3 cm thick disks

Table 1. Stem diameter, tree height, stem volume, and stress-wave velocity of the stems of three species.

Species	Tree number	Stem diameter (cm)	Tree height (m)	Stem volume (m ³)	Stress-wave velocity (km s ⁻¹)
<i>A. mangium</i>	1	20.8	16.9	0.156	3.50
	2	24.3	21.5	0.314	3.52
	3	27.0	22.8	0.347	3.70
	Mean	24.0	20.4	0.272	3.57
	SD	3.1	3.1	0.102	0.11
	Annual increment	3.4	2.9	0.039	–
<i>M. eminii</i>	1	19.6	20.4	0.196	3.18
	2	26.6	17.8	0.332	3.20
	3	26.2	17.9	0.307	3.12
	Mean	24.1	18.7	0.278	3.17
	SD	3.9	1.5	0.072	0.04
	Annual increment	3.4	2.7	0.040	–
<i>M. azedarach</i>	1	29.3	21.6	0.465	4.09
	2	25.2	21.3	0.341	3.93
	3	26.4	18.4	0.366	4.04
	Mean	27.0	20.4	0.391	4.02
	SD	2.1	1.8	0.066	0.08
	Annual increment	2.1	1.6	0.030	–

Note: Stem volume was regarded as total volume of logs obtained from 1.3 m above the ground until the top diameter of each log became less than 11 cm in each tree. Annual increments of stem diameter, tree height, and stem volume were calculated from the mean values divided by tree age (7 years old for *A. mangium* and *M. eminii*, and 13 years old for *M. azedarach*). – = not calculated; SD = standard deviation.

collected at 2 m interval from 1.3 m to 11.3 m above the ground. Wedge-shape specimens with 30° centre angles were prepared from the disks (Fig. 1C). The wedge-shape specimens were cut again at 1 cm intervals from the pith to bark to determine the radial variation of basic density. Basic density was calculated by dividing the oven-dry weight by green volume determined using the water displacement method.

To measure the compressive strength parallel to grain and static bending properties, 10 cm thick disks were collected at 2 m intervals from 1.3 m to 11.3 m above the ground in all nine trees (Fig. 1D). Bark-to-bark radial boards (with pith, 10 cm thickness) were collected from the disks. Then the boards were air-dried in a laboratory at 20 °C and 65 % relative humidity. The boards were cut in half at the pith position, and then the radial boards (from pith to bark) were processed into boards of two different thicknesses (4 mm and 20 mm in the tangential direction). After that, the boards were again cut successively at 20 mm intervals in the radial direction from the pith to bark side.

Finally, a total of 429 compressive test specimens (20 (R) × 20 (T) × 40 (L) mm) and 429 bending specimens (20

(R) × 4 (T) × 65 (L) mm) were prepared. Before the tests, the size and weight of the specimens were determined to calculate air-dry density at testing. In addition, the oven-dry weight of the specimen heated at 105 °C was measured after the tests to measure the moisture content at testing.

Compressive tests were conducted using a universal testing machine (RTF-2350, A&D) with a load speed of 0.5 mm/min and a cross-section area. Compressive strength parallel to grain (σ) was calculated from the following equation:

$$\sigma \text{ (MPa)} = P/A \quad (2)$$

where, P (N) is the maximum load, and A (mm²) is the cross-sectional area of the specimen.

The static bending tests were conducted using a universal testing machine (MSC-5/200-2, Tokyo Testing Machine). A load was applied to the centre of the specimen on the radial surface with a 56 mm span and 0.5 mm/min load speed. The load and deflection were recorded using a personal computer. The MOE and MOR were calculated using the following formulas:

Fig. 1. Illustration of experimental procedure and sample preparations.

Note: A, After measuring the growth characteristics and stress-wave velocity, trees were harvested and then cut into 2 m in length; B, after measuring the dynamic Young's modulus of logs and taper, two types of disks were obtained for measuring the wood properties; C, preparation of samples for basic density; D, preparation of samples for compressive strength and static bending tests; E, methods for simulation of the modulus of elasticity (MOE) of lamina.

$$\text{MOE (GPa)} = (\Delta P l^3 / 4 \Delta Y b h^3) \cdot 10^{-3} \quad (3)$$

$$\text{MOR (MPa)} = 3 P l / 2 b h^2 \quad (4)$$

where, l (mm) is the length of the span, ΔP (N) is the difference of load between 10 % and 40 % values of the maximum load, ΔY (mm) is deflection due to ΔP , b (mm) is the width of the specimen, h (mm) is the height of the specimen, and P (N) is the maximum load.

Simulation of the modulus of elasticity in laminae and glulam

Figure 1E shows the method of simulation used for the MOE of the laminae. The size of the simulated lamina was 30×150 mm in cross section and 2000 mm in length. Production of the laminae was carried out on the obtained 2 m long logs. In this simulation, as many laminae as possible were produced from the logs. To simulate the MOE in each lamina, mean values of MOE in each radial position in a log were determined by averaging the MOE values of small-clear specimens obtained from both ends of a log (as described above, MOE of small-clear specimens were obtained at 2 m intervals in longitudinal direction). Then, MOE in each lamina was calculated as area-weighted MOE (Fig. 1E). Based on the simulated results, the laminae

were graded by 1 GPa intervals.

Using the simulated laminae, the MOE of six-layer glulam (cross-section of 90 mm w $\times$ 150 mm h; cross-section of each layer = 90 mm $\times$ 25 mm) made from a single species was simulated based on the number of laminae obtained from each species. The MOE of glulam (E_{GL}) was calculated using the following formula (Hayashi 1989):

$$E_{GL} \text{ (GPa)} = \sum E_{Li} I_i / I \quad (5)$$

where E_{Li} (GPa) is the MOE of the i th lamina, I_i (mm⁴) is second moments of area in i th lamina, and I (mm⁴) is second moments of area in glulam ($bh^3/12$, where b is the width and h is the height of glulam).

Two types of glulam made of single species were simulated: type I) glulam produced with randomly selected laminae, and type II) glulam produced with graded laminae. For type I, laminae were sorted into 100 patterns in order of random numbers created by the 'sample' function of the R software (R Core Team 2020). A total of 100 lamination simulations for the MOE of glulam were conducted in each species. For type II, the laminae of a species were divided into three groups (high, medium, and low) with almost the same number of lamina. The lamina was sorted by descending order of MOE in each species. The upper and lower about 1/3 number of total lamina in this order was regarded as lamina belonging to 'high' and 'low' groups. Remained lamina was regarded as 'medium' group. The high,

medium, and low MOE groups of laminae were used for the outer (first and sixth), middle (second and fifth), and inner (third and fourth) layers of six-layered glulam, respectively. A total of 100 lamination simulations were also conducted in each MOE group of a species according to the same method used for type I glulam. If a shortage of laminae occurred in the middle or inner layers, the laminae for those layers were replaced with laminae from the outer or middle layers, respectively.

Data analysis

The mean values of each individual tree were calculated by averaging the values obtained from radial variations or axial variations. All statistical analyses were conducted using the R software (R Core Team 2020). A one-way analysis of variance test was applied to evaluate the differences within or among species in wood properties. Tukey's HSD test was also applied when significant differences were found within or among species.

Linear mixed model (LMM) with the distance from the pith (1-cm intervals) as a fixed effect was used to clarify the radial variation of wood properties. To consider the effect of tree differences (random tree effect), two different linear mixed models were prepared; both intercept and slope had random tree effect, or only intercept had random tree effect. In both models, mean value and variance in the random variable of trees were regarded as 0, and $\sigma_{\text{intercept}}$ or σ_{slope} , respectively.

Akaike information criterion (AIC) was used as the goodness of fit of the model to evaluate the random tree effect on the intercept or slope in two linear mixed models (Akaike 1998). The model with smaller AIC value was assigned as the radial variation of the wood properties. The model evaluation was conducted for each species using lme4 package for R (Bates et al. 2015).

RESULTS AND DISCUSSION

Stress-wave velocity of stem and log characteristics

The mean stress-wave velocity of stems for *A. mangium*, *M. eminii*, and *M. azedarach* were 3.57, 3.17, and 4.02 km s⁻¹, respectively (Table 1). In previous studies, the mean values of the stress-wave velocity of stems were reported to be 3.59 and 3.75 km s⁻¹ in five- and seven-year-old *A. mangium* trees in West Java, Indonesia (Makino et al. 2012), and 3.27 km s⁻¹ in seven-year-old *M. eminii* trees in

West Java, Indonesia (Karlinasari et al. 2018). The stress-wave velocity values in *A. mangium* and *M. eminii* were similar to those reported by other researchers on the same species. Thus, Young's modulus of wood from these species of community forest in Indonesia are similar to those in previous studies.

The mean values of taper, green density, and DMOE of logs for the three species are presented in Table 2. The mean values of log taper were 1.03, 0.82, and 0.96 cm m⁻¹ for *A. mangium*, *M. eminii*, and *M. azedarach*, respectively. No significant differences in taper were found among the trees in each species, suggesting that, of the three species, *M. eminii* produces the most cylindrical logs from the base to the top. The mean values of green density of each tree ranged from 1.02 to 1.08, 0.63 to 0.77, and 0.69 to 0.75 g cm⁻³ for *A. mangium*, *M. eminii*, and *M. azedarach*, respectively. Significant differences in green density and the DMOE of logs were found among the *A. mangium* and *M. eminii* trees, but not for *M. azedarach*. Mean DMOE value was highest in *A. mangium* (11.70 GPa), followed by *M. azedarach* (9.98 GPa), and *M. eminii* (7.96 GPa). However, no differences were found among species due to large variation of DMOE within species for *A. mangium* and *M. eminii*. It suggested that selecting the trees in these species is important for producing the wood with high Young's modulus in these species.

Wood properties

The mean values of basic density, compressive strength parallel to grain, MOE, and MOR the whole trees were 0.43 g cm⁻³, 42.4 MPa, 8.92 GPa, and 97.3 MPa for *A. mangium*, 0.33 g cm⁻³, 30.6 MPa, 6.84 GPa, and 72.7 MPa for *M. eminii*, and 0.44 g cm⁻³, 39.7 MPa, 8.36 GPa, and 90.3 MPa for *M. azedarach* (Table 3). With a few exceptions, the mean values of wood properties obtained in the present study were in the range of the values reported by previous researchers (Table 4, Chowdhury et al. 2009; Zziwa et al. 2010; Makino et al. 2012; Jusoh et al. 2014; Duong and Matsumura 2018a, b; Duong et al. 2019).

Although mean values were different among species, no significant differences among species were found in compressive strength, MOE, and MOR (Table 3). However, basic density was significantly differed among species. Of three trees in a species, *M. azedarach* showed no significant differences among trees in all wood properties, while significant differences among trees were found in *A. mangium* and *M. eminii* for all wood properties (Table 3). Therefore, when wood from these species were used for

Table 2. Log characteristics of three species.

Species	Tree number	<i>n</i>	Taper (cm m ⁻¹)		Green density (g cm ⁻³)		DMOE (GPa)	
			Mean	SD	Mean	SD	Mean	SD
<i>A. mangium</i>	1	4	1.19 ^a	0.33	1.08 ^a	0.02	11.62 ^b	1.51
	2	5	0.86 ^a	0.31	1.02 ^b	0.03	9.34 ^c	0.36
	3	5	1.05 ^a	0.26	1.07 ^a	0.02	14.15 ^a	0.79
	Mean	3	1.03 ^(a)	0.16	1.06 ^(a)	0.03	11.70 ^(a)	2.41
<i>M. eminii</i>	1	4	0.45 ^a	0.15	0.63 ^b	0.10	7.76 ^b	0.91
	2	5	1.05 ^a	0.85	0.67 ^a	0.05	6.97 ^b	0.41
	3	4	0.97 ^a	0.28	0.77 ^a	0.04	9.16 ^a	0.27
	Mean	3	0.82 ^(a)	0.33	0.69 ^(b)	0.08	7.96 ^(a)	1.11
<i>M. azedarach</i>	1	5	1.08 ^a	0.86	0.75 ^a	0.04	10.39 ^a	0.95
	2	5	0.73 ^a	1.07	0.69 ^a	0.09	8.85 ^a	1.80
	3	5	1.07 ^a	0.47	0.73 ^a	0.07	10.69 ^a	1.32
	Mean	3	0.96 ^(a)	0.20	0.72 ^(b)	0.03	9.98 ^(a)	0.99

Note: *n* = number of logs in each tree or number of trees for mean value in each species; SD = standard deviation; DMOE = dynamic Young's modulus of logs. The same alphabet letters used after values indicate no significant differences between the trees in each species based on Tukey's HSD test at 5 %. The same alphabet letters in parenthesis used after mean values indicate no significant differences among species based on Tukey's HSD test at 5 %.

Table 3. Mean and standard deviation of wood properties in whole trees.

Species	Tree number	BD (g cm ⁻³)			CS (MPa)			MOE (GPa)			MOR (MPa)		
		<i>n</i>	Mean	SD	<i>n</i>	Mean	SD	<i>n</i>	Mean	SD	<i>n</i>	Mean	SD
<i>A. mangium</i>	1	33	0.46 ^a	0.05	32	43.5 ^b	3.9	32	9.48 ^a	1.89	32	105.6 ^a	20.5
	2	50	0.37 ^b	0.05	49	34.4 ^c	5.6	49	7.03 ^b	1.86	49	72.6 ^b	18.6
	3	52	0.47 ^a	0.09	52	49.3 ^a	9.3	52	10.24 ^a	2.25	52	113.6 ^a	25.0
	Mean	3	0.43 ^(a)	0.06	3	42.4 ^(a)	7.5	3	8.92 ^(a)	1.68	3	97.3 ^(a)	21.7
<i>M. eminii</i>	1	37	0.29 ^c	0.03	38	27.1 ^b	3.6	38	6.56 ^b	1.72	38	66.7 ^b	12.0
	2	55	0.34 ^b	0.06	51	27.8 ^b	2.8	51	6.24 ^b	1.33	51	67.2 ^b	12.3
	3	48	0.37 ^a	0.06	47	37.0 ^a	4.4	47	7.72 ^a	1.53	47	84.1 ^a	20.5
	Mean	3	0.33 ^(b)	0.04	3	30.6 ^(a)	5.5	3	6.84 ^(a)	0.78	3	72.7 ^(a)	9.9
<i>M. azedarach</i>	1	63	0.44 ^a	0.04	59	40.8 ^a	5.7	59	9.09 ^a	2.03	59	95.3 ^a	27.5
	2	56	0.43 ^a	0.05	49	38.7 ^a	7.0	49	7.99 ^a	2.19	49	85.7 ^a	47.0
	3	53	0.44 ^a	0.08	52	39.6 ^a	4.4	52	8.00 ^a	1.54	52	89.9 ^a	29.8
	Mean	3	0.44 ^(a)	0.01	3	39.7 ^(a)	1.1	3	8.36 ^(a)	0.63	3	90.3 ^(a)	4.8

Note: *n* = total number of samples obtained from different height positions in each tree or the total number of trees for the mean value in each species; BD = basic density; CS = compressive strength parallel to grain; MOE = modulus of elasticity; MOR = modulus of rupture; SD = standard deviation. The same alphabet letters used after values indicate no significant differences between the trees based on Tukey's HSD test at 5 %. The same alphabet letters in parenthesis used after mean values indicate no significant differences between the species based on Tukey's HSD test at 5 %. Air-dry density and moisture content of compressive strength at testing were 0.44 g cm⁻³ and 11.4 %, 0.35 g cm⁻³ and 9.8 %, and 0.45 g cm⁻³ and 11.4 % for *A. mangium*, *M. eminii*, and *M. azedarach*, respectively. Air-dry density and moisture content of at static bending strength test were 0.46 g cm⁻³ and 11.5 %, 0.36 g cm⁻³ and 10.6 %, and 0.47 g cm⁻³ and 11.9 % for *A. mangium*, *M. eminii*, and *M. azedarach*, respectively.

structural members, tree selection within species is important for *A. mangium* and *M. eminii* to obtain the wood with suitable physical and mechanical properties for

structural members.

Figure 2 shows radial variations of basic density, compressive strength, MOE, and MOR at 1.3 m above the

Table 4. Comparison of wood properties of *Acacia*, *Maesopsis*, and *Melia* species in previous studies with those in the present study.

Species	Tree age (year)	BD (g cm ⁻³)	CS (MPa)	MOE (GPa)	MOR (MPa)	References
<i>A. mangium</i>	7	0.43	42.4	8.92	97.3	This study
<i>A. mangium</i>	5 and 7	0.42 and 0.45	ND	ND	ND	Makino et al. (2012)
<i>A. mangium</i>	10, 15 and 20	0.52, 0.56, and 0.60	ND	ND	ND	Chowdhury et al. (2005)
<i>A. auriculiformis</i>	11	0.57	66	ND	ND	Chowdhury et al. (2009)
<i>A. auriculiformis</i>	11	ND	ND	8.5	119.8	Chowdhury et al. (2012)
<i>A. mangium</i>	7	0.46	53	9.99	78.0	Jusoh et al. (2014)
<i>A. auriculiformis</i>	7	0.64	59	8.21	89.0	Jusoh et al. (2014)
<i>M. eminii</i>	7	0.33	30.6	6.84	72.7	This study
<i>M. eminii</i>	Unknown	0.41	26.9	ND	ND	Zziwa et al. (2010)
<i>M. azedarach</i>	13	0.44	39.7	8.36	90.3	This study
<i>M. azedarach</i>	17 to 19	ND	ND	9.26	78.6	Duong and Matsumura (2018a)
<i>M. azedarach</i>	17 to 19	0.43	ND	ND	ND	Duong and Matsumura (2018b)
<i>M. azedarach</i>	17 to 19	ND	38.3	ND	ND	Duong et al. (2019)

Note: BD = basic density; CS = compressive strength parallel to grain; MOE = modulus of elasticity; MOR = modulus of rupture; ND = no data.

ground. In previous reports, radial patterns of these wood properties of increasing from the pith to the bark have been found in *A. mangium* (Makino et al. 2012), *Acacia auriculiformis* grown in Bangladesh (Chowdhury et al. 2009, 2012), and *M. azedarach* grown in Northern Vietnam (Duong and Matsumura 2018a, b; Duong et al. 2019). In the present study, two LMMs were fitted on the radial variations of wood properties (Fig. 2). As the results, the LMM with random tree intercept were fitted to radial variation of basic density, MOE, and MOR in three species, except for basic density of *A. mangium* and MOR of *M. eminii*. For radial variation of these exceptions and compressive strength of three species, LMM with random tree intercept and slope were fitted. These regression lines obtained in all wood properties for three species showed increasing trends from pith to bark, suggesting that strength properties of wood in three tested species were higher values in bark side compared to pith side. Similar radial patterns were also found at the other height positions in three species with several exceptions (Figs. 3 to 6), suggesting that radial variations of physical and mechanical properties at different heights in three species might be estimated by the determination of radial variations of these wood properties at 1.3 m above the ground with several exceptions.

Relationships between air-dry density and wood properties

Table 5 shows the correlation coefficients between air-dry density and wood properties for the three species. Air-

dry density showed significant positive correlations with compressive strength, MOE, and MOR in all species. In addition, the MOE was also positively correlated with the MOR in all species. A previous study found a positive correlation between wood density and compressive strength in *A. mangium* (Makino et al. 2012) and *A. auriculiformis* (Chowdhury et al. 2009). In addition, wood density has also been found to be correlated with the MOE and MOR in *M. azedarach* (Duong and Matsumura 2018a) and Uganda timber species (Zziwa et al. 2010). Another study found a high positive correlation between the MOE and MOR ($r = 0.81$) in *M. azedarach* (Duong and Matsumura 2018a). Based on the results of the present study, air-dry density is considered to be a good predictor of the mechanical properties of the three fast-growing tree species. In addition, the MOR also can be predicted by the MOE.

The relationship between stress-wave velocity, the dynamic Young's modulus, and the modulus of elasticity

In general, there is a significant positive correlation between the stress-wave velocity of stems and the DMOE of logs (Wang et al. 2001; Ishiguri et al. 2007). The DMOE of logs is also positively correlated with the MOE (Duong and Matsumura 2018a). In the present study, the highest mean value of stress-wave velocity was recorded for *M. azedarach* (4.02 km s⁻¹), followed by *A. mangium* (3.57 km s⁻¹), and *M. eminii* (3.17 km s⁻¹) (Table 1). However, the highest mean DMOE value was obtained from *A. mangium* (11.70 GPa), followed by *M. azedarach* (9.98 GPa), and *M. eminii* (7.96 GPa) (Table 2). In addition, the MOE under the

Fig. 2. Radial variations of wood properties at 1.3 m above the ground.

Note: Circles, squares, and triangles indicate the data of tree No. 1, 2, and 3, respectively. Solid lines indicate regression lines of liner mixed models with random intercept and/or slope. BD = basic density; CS = compressive strength parallel to grain; MOE = modulus of elasticity; MOR = modulus of rupture.

air-dry condition showed higher values for *A. mangium* (8.92 GPa) and *M. azedarach* (8.36 GPa) but showed a relatively lower value for *M. eminii* (6.84 GPa) (Table 3).

To clarify the differences in species order among the properties, the ratio of mean value in each species was calculated by the mean value of the lowest species as 1. The results are shown in Fig. 7. Among three species, *M. eminii* showed the lowest mean values. However, the highest stress-wave velocity and DMOE values were found in different species: the highest stress-wave velocity of stems ratio was found in *M. azedarach* (1.27), and the highest DMOE value was found in *A. mangium* (1.47). Nevertheless, *A. mangium* and *M. azedarach* showed almost the same ratio (about 1.22 and 1.30) for MOE, suggesting that underestimation of the stress-wave velocity of stems and overestimation of the DMOE of logs occurred

in *A. mangium*.

Yamamoto et al. (2003) confirmed a high green moisture content in the heartwood of *A. mangium* grown in three Asian countries; the highest moisture contents were 253 % and 149 % in the inner heartwood and sapwood, respectively. Thus, in *A. mangium*, the high value of green moisture content resulted in high green density. Overestimation of the DMOE of logs in green conditions might occur due to a high green density of logs. At the same time, Kodama (1992) found that the ultrasonic wave velocity of wood largely decreased below the fibre saturation point (about 30 % moisture content) and also gradually decreased with an increase of moisture content over the fibre saturation point. Thus, underestimation of the stress-wave velocity of *A. mangium* stems might also be affected by high green moisture content. Based on these results,

Fig. 3. Within-tree variations of basic density in three species.

Fig. 4. Within-tree variations of compressive strength parallel to grain in three species.

Fig. 5. Within-tree variations of modulus of elasticity in three species.

Fig. 6. Within-tree variations of modulus of rupture in three species.

Table 5. Relationship between air-dry density and wood properties.

Species	n	Factor 1	Factor 2	Correlation coefficient
<i>A. mangium</i>	133	AD	CS	0.888**
			MOE	0.844**
			MOR	0.934**
		MOE	MOR	0.885**
<i>M. eminii</i>	136	AD	CS	0.848**
			MOE	0.671**
			MOR	0.865**
		MOE	MOR	0.827**
<i>M. azedarach</i>	160	AD	CS	0.648**
			MOE	0.722**
			MOR	0.737**
		MOE	MOR	0.875**

Note: n = total number of samples obtained from different height positions in each species; ** = $p < 0.01$.

Fig. 7. The ratio of mean values in each wood property in three species.

Note: SWV = stress-wave velocity of stems; DMOE = dynamic Young's modulus of logs; MOE = modulus of elasticity of small-clear specimens. The ratio was calculated by the mean value of the lowest value among three species as 1. Dotted line indicates the ratio of 1. Bars indicate standard deviation.

confirming the moisture content of wood is considered important when applying non-destructive testing methods to estimate the static bending properties of *A. mangium*.

The modulus of elasticity of lamina and glulam

Figure 8 shows the number and cumulative frequency of the simulated MOE of laminae for each species. Thirty-five, 45, and 62 simulated laminae were obtained from *A. mangium*, *M. eminii*, and *M. azedarach* logs, respectively.

The range of simulated MOE classes of the laminae was similar in *A. mangium* and *M. azedarach* (6 to 10 or 11 GPa), whereas it was lower in *M. eminii* (about 5 to 8 GPa) (Fig. 8). The mean simulated MOE values of the laminae were 8.93, 6.82, and 8.63 GPa for *A. mangium*, *M. eminii*, and *M. azedarach*, respectively (Fig. 8).

Five, seven, and 10 glulams made of single species were simulated from the laminae of *A. mangium*, *M. eminii*, and *M. azedarach*, respectively. For type I glulam, the MOE ranged from 6.89 to 11.16, 5.63 to 8.22, and 7.01 to 10.27 GPa in *A. mangium*, *M. eminii*, and *M. azedarach*, respectively (Fig. 9). The mean values were 8.94, 6.82, and 8.66 GPa respectively (Fig. 9). These mean values were similar to the MOE values of small-clear specimens (Table 3).

For type II glulam, laminae in each species were divided into three groups for use in the outer (first and sixth), middle (second and fifth), and inner (third and fourth) layers of glulam. The results showed that the MOE classes of the laminae for the outer, middle, and inner layers were 10 to 11 GPa, 8 to 9 GPa, and 6 to 7 GPa for *A. mangium*; 7 to 8 GPa, 6 GPa, and 5 GPa for *M. eminii*; and 9 to 10 GPa, 8 GPa, and 6 to 7 GPa for *M. azedarach*, respectively (Fig. 8). The results of the simulated MOE in type II are listed in Fig. 9. The MOE ranged from 9.55 to 10.81, 6.79 to 8.19, and 8.75 to 10.42 GPa in *A. mangium*, *M. eminii*, and *M. azedarach*, respectively. The mean values were 10.20, 7.28, and 9.39 GPa in each species, respectively, which resulted in the MOE increasing about 5 % to 15 % compared to type I glulam.

The increase effects by lamination of different MOE laminae were found especially in the minimum value for each species (Fig. 9), suggesting that sorting of laminae can increase the MOE of glulam made of single species. In

Fig. 8. Number and cumulative frequency of laminae in each simulated MOE class.

Note: n = number of laminae; SD = standard deviation; min. = minimum; max. = maximum. The MOE of laminae was classified into each 1 GPa intervals.

addition, the range from minimum to maximum mean values for type II glulam was narrower than it was in type I for all species (Fig. 9). These results indicate that variation in MOE values in glulam is reduced by lamination of graded laminae. Further research is needed to produce actual size glulam to confirm the simulated results obtained in the present study. In addition, glulam made of different species should be also considered for future experiments.

Fig. 9. Box-and-whisker plots of the simulated MOE of six-layered glulam made of a single species.

Note: Lower and upper whiskers indicate lower and maximum values of simulated MOE in glulams. Boxes indicate lower quartile, median, and upper quartile. Circles indicate mean values of the simulated MOE in glulams. Values in parenthesis indicate an increasing ratio of mean values in type I to type II. A total of 100 combinations of lamination simulation in each species and glulam type were conducted. In one lamination simulation, the MOE values of 5, 7, and 10 glulam beams were simulated for *A. mangium*, *M. eminii*, and *M. azedarach*, respectively. Values in each plot indicate results of 100 lamination simulations (each simulation has mean, minimum, and maximum values of simulated MOE in each species). Type I was glulam laminated with randomly selected laminae, and type II was glulam composed of three different MOE laminae (outer = first and sixth layers, middle = second and fifth layers, and inner = third and fourth layers; The highest MOE lamina was the outer layer followed by the middle and inner layers).

CONCLUSIONS

The present study investigated the stress-wave velocity of stems, log characteristics (taper, green density, and dynamic Young's modulus), and wood properties (basic density, compressive strength parallel to grain, MOE, and MOR) of three fast-growing tree species grown in community forests in Yogyakarta, Java island, Indonesia: *A. mangium*, *M. eminii*, and *M. azedarach*. To consider the wider utilizations of the wood, the MOE values of laminae and glulam were simulated. The mean basic density values, compressive strength parallel to grain, MOE, and MOR of *A. mangium* and *M. azedarach* were about 0.45 g cm⁻³, 40 MPa, 8 to 9 GPa, and 90 to 100 MPa. Those of *M. eminii* were about 0.33 g cm⁻³, 30 MPa, 7 GPa, and 70 MPa. Regression lines for radial variations of these wood properties showed increasing trends from pith to bark at 1.3 m above the ground for three species. Significant positive correlations between air-dry density and compressive strength, MOE, and MOR were found in all species, suggesting that air-dry density is a good indicator for predicting the mechanical properties of wood for these three species. For the simulation of the MOE of the laminae, mean values were 8.93, 6.82, and 8.63 GPa for *A. mangium*, *M. eminii*, and *M. azedarach*, respectively. The simulated MOE values of glulam composed of graded laminae (type II in the present study) were 10.20, 7.28, and 9.39 GPa, respectively, being increased by a ratio of about 5 % to 15 % compared to those of randomly laminated glulam (type I in the present study). It is concluded, therefore, that the grading of laminae is effective for producing glulam with higher MOE.

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