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ORIGINAL ARTICLE

**Eka Mulya Alamsyah · Liu Chang Nan · Masaaki Yamada
Kinji Taki · Hiroaki Yoshida**

Bondability of tropical fast-growing tree species I: Indonesian wood species

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Abstract To estimate the potential bonding performance of bonded wood products from tropical fast-growing tree species, a study on the bondability of *Paraserianthes falcataria* L. Nielsen, *Pinus merkusii* Jungh et. De. Vriese, and *Acacia mangium* Willd from Indonesia was conducted. Two-ply laminations were produced using polyvinyl acetate emulsion (PVAc), urea formaldehyde (UF), resorcinol formaldehyde (RF), and water-based polymer isocyanate (API) adhesives. In order to determine the bonding performance, the block-shear test was applied according to the Japanese Agricultural Standard for structural glued laminated timber under normal conditions and after accelerated-aging treatments. To support this study, the wettability of each wood species was also investigated through contact-angle measurement. The results showed that the bonding performance of low-density *P. falcataria* was better than that of medium-density *P. merkusii* and medium-density *A. mangium*, while the bonding performance of medium-density *P. merkusii* was better than that of medium-density *A. mangium*. Furthermore, compared with *A. mangium*, the small contact angle and good wettability in *P. falcataria* and *P. merkusii* result in better adhesion and more intimate contact between the wood surfaces and adhesive.

E.M. Alamsyah · L.C. Nan
The United Graduate School of Agricultural Science, Gifu University (Participating University: Shizuoka University), Gifu, Japan

M. Yamada · K. Taki (✉)
Wood Adhesion Laboratory, Faculty of Agriculture, Shizuoka University, 836 Ohya, Shizuoka 422-8529, Japan
Tel. +81-54-238-4860; Fax +81-54-238-4860
e-mail: afktaki@agr.shizuoka.ac.jp

H. Yoshida
Shizuoka University, Shizuoka 422–8529, Japan

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Key words Bondability · Tropical fast-growing · Indonesian wood species

Introduction

Since fast-growing tree species have become a popular plantation forest commodity not only in Indonesia but also in other Asian countries, many studies have been conducted on their properties and possible utilization. In Indonesia, most of these fast-growing tree species were initially selected to provide the raw materials for pulp and paper production due to their small log diameter characteristics. However, in recent years, many studies have indicated that these fast-growing tree species also have potential for further utilization for other wood products and bonded wood products due to their rapid growth rate, availability, renewable nature, high productivity, and multiple uses.[1–3] There has been much research regarding the effective use of these fast-growing tree species for wood products and bonded wood products, such as laminated veneer, veneer and plywood,[4] medium density fiberboard (MDF),[3,5] particleboard,[3] laminated veneer lumber (LVL),[3] and light structural members in buildings including glued laminated timber.[6,7]

In the future, especially in Indonesia, glulam is the bonded wood product that is deserving of the most promotion. This is because glulam can be utilized as a structural component for housing construction or as a light structural component in buildings, replacing solid wood products from the natural forest, which have become limited in supply due to extensive logging, forest fire, and other factors. Furthermore, glulam is considered to be the best alternative material for larger structural components, because it can be manufactured from small laminating lumbers.[8,9] However, extensive information on the effective utilization of these fast-growing tree species for glulam production related to its bonding performance is still limited. Some previous studies on the bonding performance of the tropical fast-growing tree species from Malaysia were reported by Hirabayashi and Nakano.[10,11] This article reports the investigation of the bonding performance and wettability of tropical fast-growing tree species from Indonesia.

Materials and methods

Materials

Wood species

Eight-year-old *Paraserianthes falcataria* L. Nielsen with 0.34 g/cm^3 air-dry density and 9% moisture content (MC), 11-year-old *Pinus merkusii* Jungh et. De. Vriese with 0.59 g/cm^3 air-dry density and 9% MC, and 7-year-old *Acacia mangium* Willd with 0.64 g/cm^3 air-dry density and 9% MC were used. They were obtained from plantation forest at Winaya Mukti University, Indonesia.

Adhesives

Four types of adhesives were used: polyvinyl acetate emulsion (PVAc, Bond CH-38, Konishi) at 200 g/m^2 spread rate, urea formaldehyde (UF, UW-061, Honen, mixed with 15 parts NH_4Cl 20%, and 10 parts wheat flour) at 300 g/m^2 spread rate, resorcinol formaldehyde (RF, J-6000, Dainihon-ink, mixed with 15 parts hardener) at 250 g/m^2 spread rate, and water-based polymer isocyanate (API, KR Bond-7800, Koyo, mixed with 15 parts cross-linking agent) at 250 g/m^2 spread rate. Mixing of the glues was done in accordance with the supplier's instructions.

Methods

Specimen preparation

All two-ply laminations were produced from laminae that contained heartwood and sapwood. Laminae measuring 230 × 120 × 10 mm with 9% air-dry MC were surface smoothened and conditioned at 20°C and 65% relative humidity (RH) for 24 h. A weighed amount of adhesive was spread on both bonding surfaces with a roller, immediately followed by close assembly. Pressure was applied at 0.98 MPa for *P. merkusii* and *P. falcataria* laminates, and at 1.18 MPa for *A. mangium* laminates at 20°C and 65% RH for 24 h of cold-pressing time. Then the laminates were conditioned at 20°C and 65% RH room for 7 days.

Block-shear test

Small block-shear specimens were cut from the two-ply laminates bonded with test adhesives. Bond strength and wood failure were measured according to the Japan Agricultural Standard for Structural Glued Laminated Timber (shear area about 6.25 cm^2)[12] under normal conditions, and after accelerated-aging treatments as shown in Table 1. As a control, the shear strength of wood was also investigated. Ten specimens were tested for each treatment (total 390 specimens). In the block-shear test, an Amsler machine was used with a load rate of about 9.8 KN/min until failure occurred. Shear strength was defined as the load at failure expressed in megapascals. Wood failure was estimated at 0%–100% of shear area. The bonding performances of the specimens were classified into four categories: excellent (80%–100% retention both of wood strength and wood failure), good (60%–79%), bad (40%–59%), and worst (0%–39%). Specimens with excellent and good bonding performances are indications of better adhesive penetration and easier bonding.

Contact-angle test

To determine the natural wettability of the wood, contact-angle tests were conducted using a contact-angle meter (CA-DT type A).[13] After surface smoothening, a specimen of 60 × 20 × 5 mm was made from each lamina of the wood. The specimen was then put on a slide glass and conditioned at 20°C and 65% RH for 24 h. Distilled water (0.20 ml, pH

Table 1. Description of accelerated aging treatments

Treatment	Symbol	Condition	Adhesive type			Method
			UF	RF	API	
Water dipping	W	Wet	O	NT	NT	Specimen submerged in cold tap water for 6 h
Water dipping–dry	WD	Dry	O	NT	NT	Specimen submerged in cold tap water for 6 h → dried at 40°C for 18 h
Hot water dipping	HW	Wet	O	NT	NT	Specimen submerged in hot water at 60°C for 6 h
Cyclic boiling	CB	Wet	NT	O	O	Specimen submerged in boiling water for 4h → submerged in cold tap water for 1 h → dried at 70° ± 3°C for 18 h → submerged in boiling water for 4 h
Vacuum pressure soaking	VPS	Wet	NT	O	O	Specimen submerged in cold tap water → evacuated at 635 mmHg for 5 min → pressurized at 5.2 ± 0.3 kgf/cm^2 for 1 h → these steps repeated
Vacuum pressure soaking–dry	VPSD	Dry	NT	O	O	Specimen submerged in cold tap water → evacuated at 635 mmHg for 5 min → pressurized at 5.2 ± 0.3 kgf/cm^2 for 1 h → these steps repeated → dried at 70° ± 3°C for 24 h

UF, urea formaldehyde; RF, resorcinol formaldehyde; API, water-based polymer isocyanate; O, tested; NT, not tested

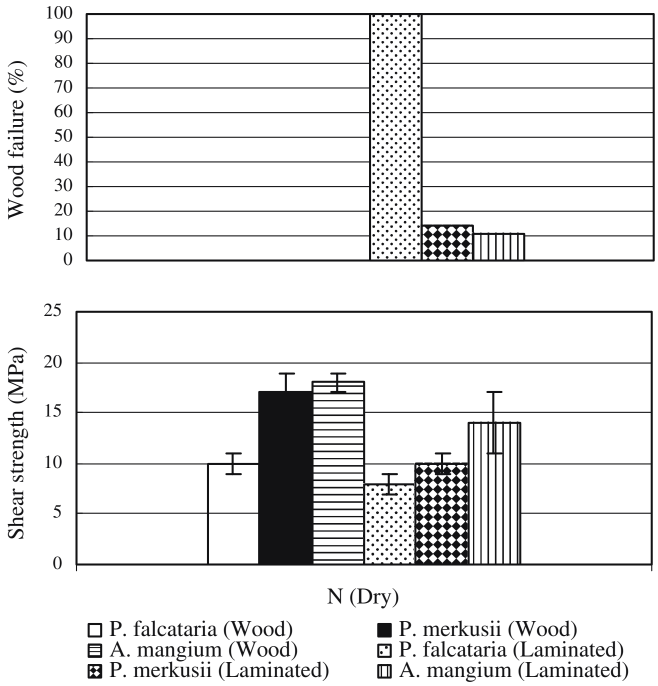

Fig. 1. Shear strength and wood failure of three Indonesian wood laminates bonded with polyvinyl acetate emulsion (PVAc) and its control specimens in normal (*N*) conditions. *Error bars* indicate standard deviation

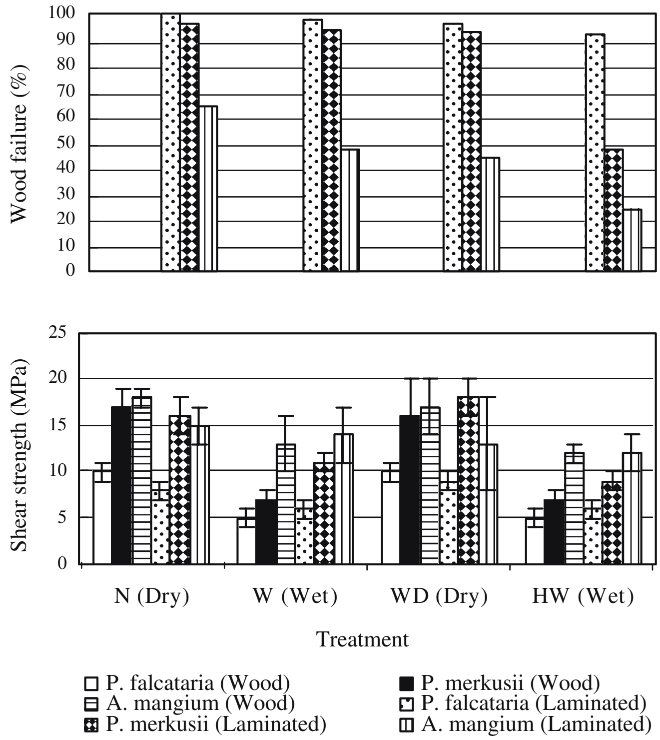

Fig. 2. Shear strength and wood failure of three Indonesian wood laminates bonded with urea formaldehyde (UF) adhesive and its control specimens in normal conditions and after accelerated-aging treatment (see Table 1 for descriptions of the accelerated-aging treatments). *N*, normal; *W*, water dipping; *WD*, water dipping–dry; *HW*, hot water dipping. *Error bars* indicate standard deviation

5.76 at room temperature 29.5°C) was dropped onto the surface. The contact-angle was observed and measured every 20 s for 2 min. Five test trials were made for each specimen.

Results and discussion

Bonding performance

The shear strength and wood failure of the three Indonesian woods are shown in Figs. 1–4. Specifically, data of bond strength, retained strength, and wood failure are summarized in Table 2.

Under normal conditions, the results showed that for laminates bonded with PVAc and API, the bond strength of *Acacia mangium* was higher than that of *Pinus merkusii* and *Paraserianthes falcataria*, while for laminates bonded with UF and RF, bond strength of *P. merkusii* was higher than that of *A. mangium* and *P. falcataria*. It seemed that the bond strengths of *A. mangium* laminates bonded with PVAc and API, and *P. merkusii* laminates bonded with UF and RF were higher than those of *P. falcataria*. However, results also showed that the percentage wood failure of *P. falcataria* was higher than those of *P. merkusii* and *A. mangium* for any adhesive tested (Figs. 1–4 and Table 2). Similar results were reported by Hirabayashi and Nakano[10] who stated that the bond strengths of *A. mangium* laminates bonded with UF, PVAc, API, and RF were higher than those of *P. falcataria*, while the percent wood failure of *P. falcataria* was higher than that of *A. mangium*.

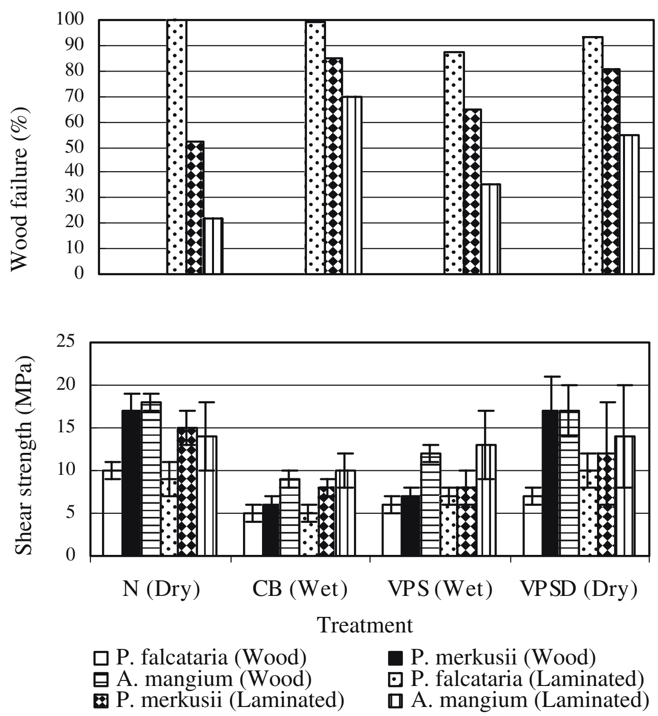

Fig. 3. Shear strength and wood failure of three Indonesian wood laminates bonded with resorcinol formaldehyde (RF) adhesive and its control specimens in normal conditions and after accelerated-aging treatment. *N*, normal; *CB*, cyclic boiling; *VPS*, vacuum pressure soaking; *VPSD*, vacuum pressure soaking–dry. *Error bars* indicate standard deviation

After accelerated-aging treatments, results showed that for laminates bonded with UF in WD (see Table 1 for descriptions of accelerated-aging treatments), the highest bond strength was achieved by *P. merkusii* followed by *A. mangium* and *P. falcataria*. In W and HW, the highest bond strength was achieved by *A. mangium* followed by *P. merkusii* and *P. falcataria*. These results indicated that for laminates bonded with UF, bond strengths of *P. merkusii* in dry conditions and *A. mangium* in wet conditions were higher than that of *P. falcataria*. However, higher wood failure was shown by *P. falcataria* followed by *P. merkusii* and *A. mangium* (Fig. 2, Table 2).

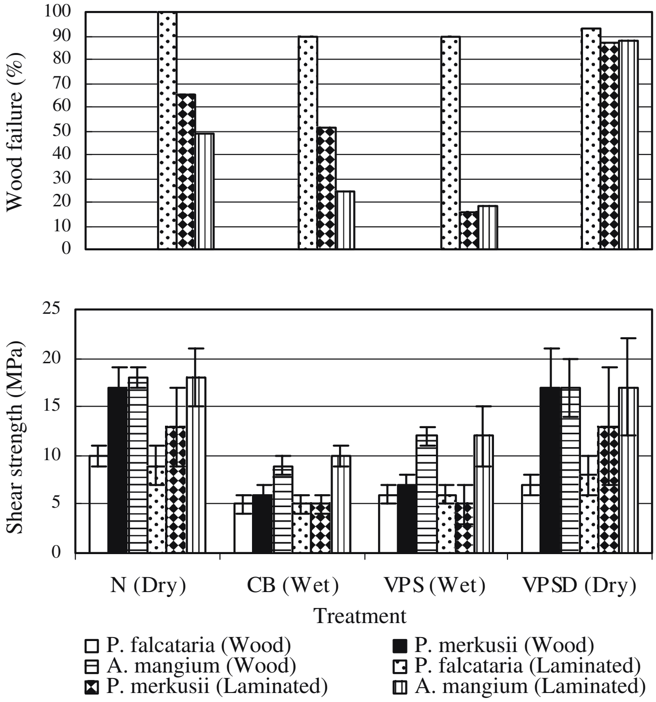

Fig. 4. Shear strength and wood failure of three Indonesian wood laminates bonded with water-based polymer isocyanate (API) and its control specimens in normal conditions and after accelerated-aging treatment. *N*, normal; *CB*, cyclic boiling; *VPS*, vacuum pressure soaking; *VPSD*, vacuum pressure soaking–dry. *Error bars* indicate standard deviation

For laminates bonded with RF in CB, VPS, and VPSD, higher bond strength was achieved by *A. mangium* followed by *P. merkusii* and *P. falcataria*. These results indicated that for laminates bonded with RF in dry and wet conditions, the bond strength of *A. mangium* was higher than those of *P. merkusii* and *P. falcataria*. In all treatments, higher wood failure was shown by *P. falcataria* followed by *P. merkusii* and *A. mangium* (Fig. 3, Table 2).

For laminates bonded with API in CB, the bond strength of *A. mangium* was higher than those of *P. merkusii* and *P. falcataria*. In VPS, higher bond strength was achieved by *A. mangium* followed by *P. falcataria* and *P. merkusii*. In VPSD, higher bond strength was achieved by *A. mangium* followed by *P. merkusii* and *P. falcataria*. These results indicated that for laminates bonded with RF with all treatments, the bond strength of *A. mangium* was higher than those of *P. merkusii* and *P. falcataria*. In wood failure, a higher percentage was shown by *P. falcataria* followed by *A. mangium* and *P. merkusii* (Fig. 4, Table 2). Hirabayashi and Nakano[10] reported that in the wet condition, the bond strength of *A. mangium* laminates bonded with UF, RF, and API was higher than that of *P. falcataria*, while the percentage of wood failure of *P. falcataria* was higher than that of *A. mangium*.

In addition, the high retention of strength and the high percentage wood failure in *P. falcataria* laminates bonded with UF (in W and HW), RF (in VPS and VPSD), and API (in VPSD) and *P. merkusii* laminates bonded with UF (in W and WD) and RF (in CB) indicated that the adhesive bond was as strong as the wood (Table 2). Vick,[14] mentioned that the best bonding performance produces a bond strength that is greater than that of the wood and wood failure of more than 75%.

Table 2. Average values of bond strength, retained strength, and wood failure

Adhesive type	Treatment[a]	Wood species								
		P. falcataria			*P. merkusii*			*A. mangium*		
		BS (MPa)	RS (%)	WF (%)	BS (MPa)	RS (%)	WF (%)	BS (MPa)	RS (%)	WF (%)
PVAc	N	8	77	100	10	59	14	14	77	11
UF	N	8	80	100	16	94	96	15	83	65
	W	6	120	98	11	157	94	14	108	47
	WD	9	90	96	18	113	93	13	76	43
	HW	6	120	92	9	129	47	12	100	24
RF	N	9	90	100	15	88	52	14	77	22
	CB	5	100	99	8	133	85	10	111	70
	VPS	7	117	87	8	114	65	13	108	35
	VPSD	10	143	93	12	71	81	14	82	55
API	N	9	90	100	13	76	65	18	100	50
	CB	5	100	90	5	83	51	10	111	24
	VPS	6	100	90	5	71	16	12	100	18
	VPSD	8	114	93	13	76	87	17	100	88

BS, bond strength; RS, retained strength (ratio of bond strength to wood strength); WF, wood failure
[a] See Table 1

Among the adhesives used under normal conditions for each wood species, results showed that in *P. falcataria*, high bond strength (9 MPa) was produced by laminates bonded with RF and API, while 100% wood failure was produced by laminates bonded with any of the adhesives tested (Table 2). These results were a little higher than those in Hirabayashi and Nakano's report.[10] In. *P. merkusii*, high bond strength (16 MPa) and high wood failure (96%) were produced by laminates bonded with UF (Table 2). In *A. mangium*, high bond strength (18 MPa) was achieved by laminates bonded with API, while high wood failure (65%) was achieved by laminates bonded with UF (Table 2). Results further showed that particularly in *A. mangium*, a low percentage of wood failure for RF (22%) indicated that RF was not yet perfectly cured after 7 days at 20°C and 65% RH. This result was in contrast to the results of Hirabayashi and Nakano[11] that in normal conditions, for *A. mangium*, higher bond strength (12.5 MPa) and higher wood failure (85%) was produced by laminates bonded with RF. The fact that the wood failure value determined by Hirabayashi and Nakano[11] was higher than that in our study indicated that their load pressurized at 1.3 MPa into laminate could develop better bonding performance than our load pressurized at 1.18 MPa. In addition, results similar to those of our study were reported by Taki et al.,[15] for a study that used selangan batu. Liu[16] reported that under normal conditions, hinoki laminates bonded with RF at 20°C and 65% RH with 7 days of curing time gave 22% wood failure, which was extended to 98% when the curing time was extended for 2 months. This indicates that particularly in Indonesian *A. mangium*, longer curing time under the conditions of 20°C and 65% RH is needed for RF. Further study is still necessary to clarify this indication.

The effects of density on the bond strength and wood failure under normal conditions, as shown in Figs. 5–7, might explain the differences in bonding performance among the wood species. In *P. falcataria* (Fig. 5), except for the laminates bonded with PVAc, the results showed that the bond strength increased with increasing laminated wood density. However, laminates bonded with any adhesive having a density ranging from 0.27 to 0.49 g/cm^3 (0.34 g/cm^3 average) gave 100% wood failure. In *P. merkusii* (Fig. 6), laminates bonded with UF increased in strength with increasing density, while for laminates bonded with PVAc, RF, and API no trend was observed. With the density of

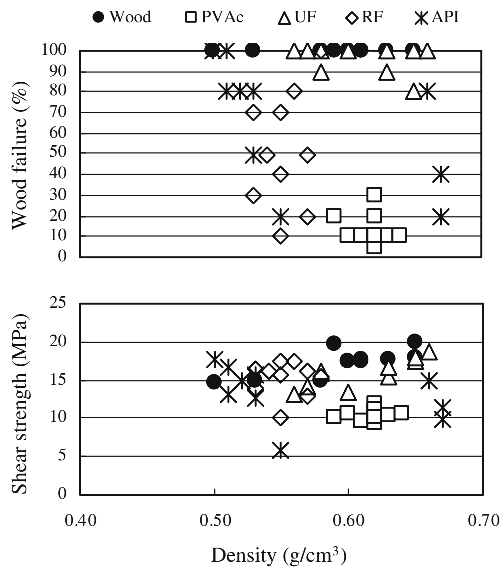

Fig. 6. Effects of density on strength and wood failure of *Pinus merkusii* laminates bonded with PVAc, UF, RF, and API and its control specimens in normal conditions

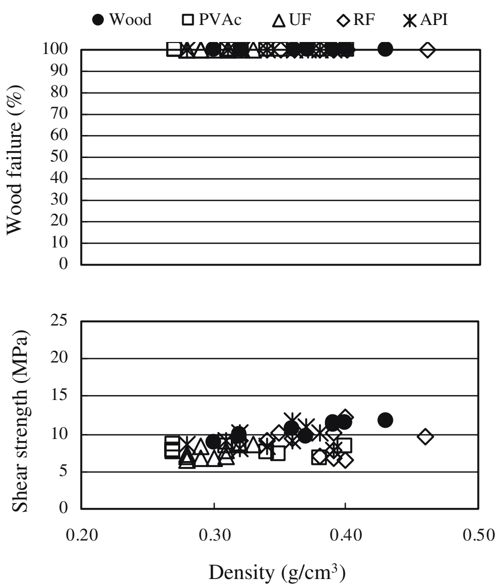

Fig. 5. Effects of density on strength and wood failure of *Paraserianthes falcataria* laminates bonded with PVAc, UF, RF, and API and its control specimens in normal conditions

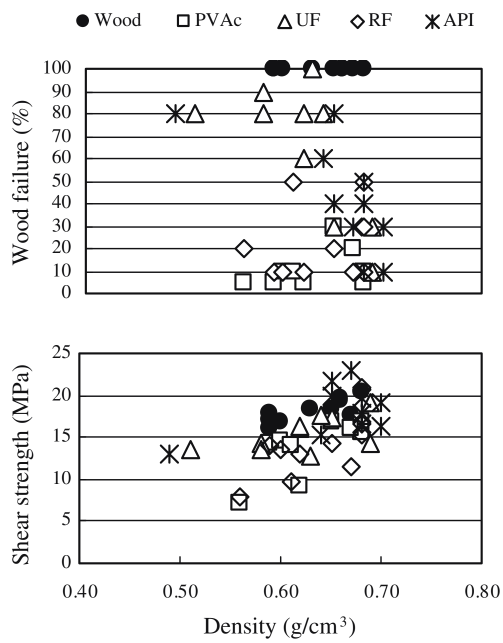

Fig. 7. Effects of density on strength and wood failure of *Acacia mangium* laminates bonded with PVAc, UF, RF, and API and its control specimens in normal conditions

laminates ranging from 0.50 to 0.67 g/cm^3 (0.59 g/cm^3 average), high percentage of wood failure was achieved particularly in laminates bonded with UF, and this tendency increased with increasing density. In *A. mangium* (Fig. 7), laminates bonded with UF increased in strength with increasing density, while for laminates bonded with PVAc, RF, and API no trend was observed. With the density of laminates ranging from 0.49 to 0.70 g/cm^3 (0.64 g/cm^3 average), high percentage wood failure, which tended to increase with increasing density, was achieved particularly in laminates bonded with UF.

The results further showed that the density varied greatly among and within the wood species. The average density of *P. falcataria* (0.34 g/cm^3) was the lowest followed by *P. merkusii* (0.59 g/cm^3), and *A. mangium* (0.64 g/cm^3). Greatest bond strength was achieved by medium-density *A. mangium* (for PVAc and API) and medium-density *P. merkusii* (for UF and RF). It seemed that the bond strength increased with increasing wood density. Otherwise, the highest percentage wood failure was achieved by low-density *P. falcataria* followed by medium-density *P. merkusii* and *A. mangium*. In addition, consistent high percentage wood failure was difficult to achieve particularly in the medium-density *A. mangium* and *P. merkusii* as compared with low-density *P. falcataria*. Furthermore, the results showed that *P. falcataria* of lower density could develop good adhesive penetration as indicated by higher values of wood failure. Mara[17] mentioned that penetration is greater in low-density woods than in high-density ones. Liquid glue lines in low-density wood lose water into the wood more quickly and become viscous, high-solids films before heat and pressure are applied. In this form, they flow less and present a more concentrated layer of adhesive solids.[18] Vick and Okkonen[19] reported that typically, wood failure of a high-density laminate such as yellow birch is lower than that of low-density wood such as Douglas fir, even though the full parallel-to-grain shear strength of both woods has been reached. As wood density increases, consistent high strength joints with high wood failure are more difficult to achieve.[14] The relationship of strength to density has two levels of significance. It includes all species and shows an upward trend in strength with increasing density.[17]

Wettability

To determine if factors other than density affect bonding performance, investigation of the wettability of *P. falcataria*, *P. merkusii*, and *A. mangium* was performed through contact-angle measurement (Fig. 8). After the water was dropped, the average contact angle of water droplets in *P. falcataria* was 8° in the heartwood, and 5° in the sapwood. In *P. merkusii* and *A. mangium*, the averages were 10° in the heartwood and 9° in the sapwood, and 46° in the heartwood and 52° in the sapwood, respectively. In addition, the water droplets on the surface of *P. falcataria* and *P. merkusii* were absorbed, and the contact angle approached zero after 50 s for *P. falcataria* and after 60 s for *P. merkusii*. On the other hand, in *A. mangium*, the drop remained as a bead on the surface, and the contact angle did not approach zero within the 2-min observation time. Hirabayashi and Nakano[10] reported that the contact angle of *A. mangium* was 70° and no decrease within the observation period was reported.

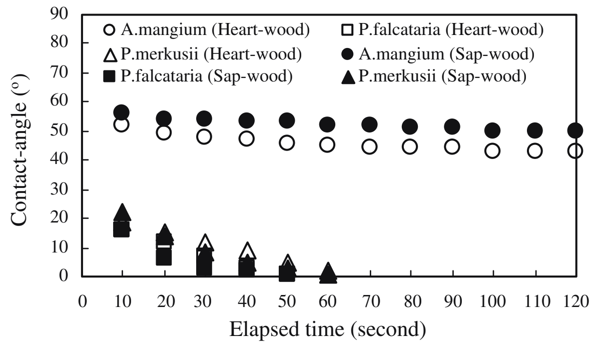

Fig. 8. Changes in contact angle of three Indonesian wood species within the 2-min observation period

The smaller contact angles for *P. falcataria* and *P. merkusii* suggested that the surfaces were easier to be wetted than that of *A. mangium*. Higher wettability of *P. falcataria* and *P. merkusii* resulted in better adhesive spread and more intimate contact between the wood surface and adhesive. Wettability of a wood surface refers to the rate of how fast a liquid can wet and spread on it.[20] It is a quick method for predicting the gluability of unknown species, and can be measured by determining the contact angle between the solid–liquid interface and liquid air surface.[21]

The results mentioned above indicated that besides density, wettability of the wood greatly affected bonding performance. Bonding performance of *P. falcataria* having low density and good wettability was far better than that of *P. merkusii* and *A. mangium*, as shown by high strength retention and high wood failure. Lastly, the bonding performance of medium-density and good wettability of *P. merkusii* was better than that of *A. mangium*. Specifically, the bonding performance of the three Indonesian woods in this study is summarized in Table 3. From this table we found that in *P. falcataria*, laminates bonded with any adhesive seemed to have better bonding performance. In *P. merkusii* and *A. mangium*, laminates bonded with UF and API seemed to have better bonding performance than PVAc and RF. Furthermore, the results in Table 3 indicated that for any adhesive used, *P. falcataria* showed better bonding performance than *P. merkusii* and *A. mangium*, while *P. merkusii* showed better bonding performance than *A. mangium*. In relation to the adhesives used, the above results showed that species that bond poorly with one adhesive may bond better with other adhesives.

Conclusions

Of the three wood species used in this study, *Paraserianthes falcataria* showed the best bonding performance followed by *Pinus merkusii*, and *Acacia mangium*. Besides its density,

Table 3. Estimation of bonding performance

Species	Adhesive type	Treatment[a]						
		N	W	WD	HW	CB	VPS	VPSD
P. falcataria	PVAc	A	NT	NT	NT	NT	NT	NT
	UF	A	A	A	A	NT	NT	NT
	RF	A	NT	NT	NT	A	A	A
	API	A	NT	NT	NT	A	A	A
P. merkusii	PVAc	D	NT	NT	NT	NT	NT	NT
	UF	A	A	A	B	NT	NT	NT
	RF	C	NT	NT	NT	A	B	A
	API	B	NT	NT	NT	C	D	A
A. mangium	PVAc	D	NT	NT	NT	NT	NT	NT
	UF	B	B	C	D	NT	NT	NT
	RF	D	NT	NT	NT	B	C	C
	API	B	NT	NT	NT	C	D	A

A, Excellent; B, good; C, bad; D, worst; NT, not tested
[a] See Table 1

wettability of the wood also greatly affected bonding performance as shown by *P. merkusii* which has medium density and good wettability as compared with *A. mangium* which has medium density and poor wettability. Furthermore, small contact angle and good wettability in *P. falcataria* and *P. merkusii* resulted in better adhesion and more intimate contact between the wood surface and adhesive. Based on the high bond strength for *A. mangium* and *P. merkusii*, it is possible to use these species for structural glulam production. However, for this possibility to be realized, further studies should be conducted in order to improve the bonding performance of the wood, especially for *A. mangium*.

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