Furfurylation Effects on Discoloration and Physical-Mechanical Properties of Wood from Tropical Plantation Forests

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ABSTRACT

Wood from tropical plantation forests has lower physical and mechanical properties than mature wood. Furfuryl alcohol (FA) impregnation into the wood could help to enhance hydrophobic properties, dimensional stability, and structural strength. Furfurylation was applied to specimens of the following four fast-growing tropical wood species: jabon (*Anthocephalus cadamba*), sengon (*Falcataria moluccana*), mangium (*Acacia mangium*), and pine (*Pinus merkusii*). The discoloration and physical and mechanical properties were subsequently measured, and the results showed that furfurylated wood had a darker color and better physical and mechanical properties than untreated wood. Specifically, the furfurylated wood had higher density, modulus of elasticity, and hardness and lower moisture content, water absorption, swelling, and shrinkage. The furfurylation significantly enhanced physical and mechanical properties.

Keywords: discoloration, furfuryl alcohol impregnation, polymerization, tropical wood, weight percent gain

1. INTRODUCTION

The demand of wood from sustainable resources increases every year, and fulfillment of consumer needs is currently dominated by wood from plantation forests. Log production in Indonesia increased by 5% each year in the period of 2015 to 2019, with the log supply for wood industry reaching 56.6 million m^3 and the value of exported forestry products reaching US$ 11.6 billion in 2019 (MoEF, 2020). Compared with mature wood, wood from forest plantations of fast-growing wood species has lower physical and mechanical properties and also lower resistance to termite attack (Hadi *et al.*, 2013, 2015, 2020). The primary advantage of fast-growing tree species is that the forest stand can be harvested in a short rotation, typically less than 10 years in tropical areas. In the future, wood from plantation forests could be used for building materials, but it needs improvement to attain high-quality performance.

Several types of chemical modifications and heat treatment of wood have been developed, such as acetylation (Hadi *et al.*, 1995); impregnation with polystyrene (Hadi *et al.*, 1998, 2016), methyl methacrylate (Cahyono *et al.*, 2020; Hadi *et al.*, 2018, 2019), 1,3-dimethylol-

4,5-dihydroxy-ethylene-urea (Militz, 1993), poisonous organic materials (Arsyad *et al*., 2019), monoethylene glycol (MEG) (Dirna *et al*., 2020), and thermosetting resin (Park and Park, 2021; Sandberg *et al.*, 2017; Sumardi *et al*., 2020); heat treatment (Esteves and Pereira, 2009); thermo-mechanical treatment (Yunianti *et al*., 2019), and furfurylation (Lande *et al*., 2004). These modifications enhance the physical-mechanical properties as well as durability of the wood, and they enable avoiding the use of toxic products. The use of furfuryl alcohol (FA) in the chemical modification of the wood requires other chemicals (e.g., a catalyst), as well as a polymerization process at several or elevated temperatures (Dong *et al.*, 2014).

According to Dong *et al.* (2014), furfurylation leads to the filling of voids in the wood, with the polymer becoming chemically bound to cell walls after polymerization. This treatment has the potential to enhance wood quality. In particular, furfurylation involves a bio-based polymer that could improve the chemical and flame resistance of wood as well as its structural strength (Karami *et al*., 2018). Dong *et al.* (2015) and Jia and Fiedler (2018) reported that furfurylation enhanced the mechanical properties, dimensional stability, and hydrophobic properties of wood. Buchelt *et al.* (2012) found that FA treatment affected the plasticization and compression capability of wood, and a previous study by Szymona *et al.* (2014) reported that the durability of low-density biomass increased 4 to 8 times in association with a medium to high weight percent gain (WPG) based on the furfurylation level. Lande *et al.* (2008) reported that furfurylation has been used in the manufacture of wood products such as furniture, construction materials, and flooring.

The FA impregnation process can affect the chemical bonds and degree of crystallinity within wood due to chemical reactions during the vacuum-pressure and polymerization processes. These changes can in turn alter the wood color and other aspects of its appearance, which are determined by the chemical compounds in its structure, including cellulose, hemicelluloses, lignin, and extractives (Aydemir *et al*., 2012). Color is one of the surface characteristics of the wood, and a discoloration is an indication of alteration in the chemical composition (Hrčková *et al*., 2018). For example, in a previous study, Hadi *et al.* (2005) showed that higher WPG due to furfurylation was associated with a darker wood color.

Polymerization of FA is induced by using various catalysts, such as citric acid (Lande *et al*., 2004), maleic anhydride (Dong *et al*., 2014), and tartaric acid (Sejati *et al.*, 2017). The utilization of tartaric acid as a catalyst for furfurylation of tropical wood species is still limited and needs to be developed. This study aimed to analyze the physical-mechanical properties of furfurylated wood from four fast-growing tropical wood species and to determine which type of wood experienced the greatest improvements.

2. MATERIALS and METHODS

2.1. Materials

Furfuryl alcohol ($\geq$ 98%) and tartaric acid (pure grade, $\geq$ 99.5%) were purchased from PT Merck Tbk (Jakarta, Indonesia). Wood from four fast-growing tropical tree species, namely jabon, sengon, mangium, and pine, was collected from forest stands in the Bogor area, Indonesia. A flat sawn pattern was used to cut the logs into timber, and wood specimens were manufactured from the timber. The dimension of wood specimen was 5 cm by 5 cm by 5 cm (width, length, and thickness) for physical properties test; 30 cm in longitudinal direction with 2 cm by 2 cm in cross section for mechanical properties (including modulus of elasticity [MOE] and modulus of rupture [MOR]); and 6 cm in longitudinal with 2 cm by 2 cm in cross section for hardness test. After the furfurylation process, the specimens were used

to determine the physical-mechanical properties of the wood. Untreated specimens were used as controls for comparison purposes.

The test specimen sizes for physical properties of wood, including density, moisture content (MC), water absorption, swelling, and shrinkage, were tested based on ASTM D 2395-07 (ASTM, 2007). British Standard 373:1957 (BS, 1957) was used as the reference for testing the mechanical properties of wood, including MOE, MOR, and hardness.

2.2. Furfurylation

Logs of jabon (*Anthocephalus cadamba*), sengon (*Falcataria moluccana*), mangium (*Acacia mangium*), and pine (*Pinus merkusii*) with a diameter less than 20 cm were harvested from a plantation forest that was less than ten years old in Bogor, Indonesia. Jabon, sengon and mangium were broadleaf, and pine was conifer which originally from Sumatra island in Indonesia. The four woods are well-known and popularly processed for wood industries.

Impregnation of FA into the wood could involve two processes. First, FA molecules interact with each other and these aggregated molecules fill the void space in the wood. Second, FA chemically reacts with wood components especially lignin (Gérardin, 2016; Hadi *et al.*, 2021). Tartaric acid was added to the FA solution at a ratio of 5:100 by weight. The air-dried wood samples were placed under vacuum at 600 mm Hg for 30 min, which was followed by immersion in FA and pressure at 10 kg/cm^2 for 30 min. The vacuum-pressure method used was based on Hadi *et al.* (2015). After FA impregnation, the specimens were wrapped in aluminum foil and heated at 100℃ for 24 hours. Afterward, the aluminum foil was opened, and the wood specimens were left under ambient conditions for 4 weeks. The weights of wood specimen before and after furfurylation process were measured to get WPG values. Ten replicate speci-

mens were prepared for each wood species and treatment.

2.3. Discoloration determination

The CIELab method was used to determine wood color. This method involved directly measuring the values of L*, a*, and b* from a photograph (which was obtained from scanning with CanonScan 4400F [Canon, Tokyo, Japan]) of the wood sample, using the ImageJ program. L* indicated lightness, with a value of 0 to 100 (black to white); a* indicated colors from green to red, with +a* from 0 to 80 corresponding to red and −a* from −80 to 0 corresponding to green; and b* indicated colors from blue to yellow, with +b* from 0 to 70 corresponding to yellow and −b* from −70 to 0 corresponding to blue (Christie, 2001). Each sample was assessed at five points, and the average values were used in the analysis. The color change (△E) was calculated according to the CIELab method (Hunter Lab, 1996), using Equation (1):

$$\triangle E = \sqrt{(\triangle L^*)^2 + (\triangle a^*)^2 + (\triangle b^*)^2} \tag{1}$$

Where
△E = color change
△L* = difference in L* values between compared samples
△a* = difference in a* values between compared samples
△b* = difference in b* values between compared samples

According to Hunter Lab (1996) and Hrčková *et al.* (2018), color change can be classified as shown in Table 1.

2.4. Physical and mechanical properties testing

The procedures for testing physical and mechanical properties were based on Hadi *et al.* (2019) as follows:

Table 1. Color change classification

Class	Color difference	Color change effect
1	$\triangle E < 0.2$	Invisible changes
2	$0.2 < \triangle E < 2.0$	Very small changes
3	$2.0 < \triangle E < 3.0$	Small changes (color changes visible by high-quality filter)
4	$3.0 < \triangle E < 6.0$	Medium changes (color changes visible by medium-quality filter)
5	$6.0 < \triangle E < 12$	Large changes (distinct color changes)
6	$\triangle E > 12$	Different color

WPG was determined by weighing the oven-dry wood specimen before treatment (W_1) and after impregnation with FA (W_2). The WPG was calculated using Equation (2):

$$WPG\ (\%) = (W_2 - W_1)\ /\ W_1 \times 100 \qquad (2)$$

MC was determined with oven-dry weight method. Each air-dry specimen was weighed to obtain its initial weight (W_3), and then it was placed in an oven at $103 \pm 2℃$ until reaching a constant weight, the oven-dry weight (W_1). The MC was calculated with Equation (3):

$$MC\ (\%) = (W_3 - W_1)\ /\ W_1 \times 100 \qquad (3)$$

Wood density was determined by measuring the volume of each wood specimen in the air-dry condition (V_1) and its oven-dry weight (W_1) and then calculating the density using Equation (4):

$$Density\ (g/cm^3) = W_1\ /\ V_1 \qquad (4)$$

Water absorption was determined by immersing the wood specimens in water at room temperature for 48 hours. Afterward, the weight (W_4) and volume (V_2) of each specimen was determined. Water absorption was determined calculating the amount of water absorbed ($W_4 - W_1$) and comparing the result with the initial oven-dry weight (W_1), according to Equation (5):

$$Water\ absorption\ (\%) = (W_4 - W_1)\ /\ W_1 \times 100 \qquad (5)$$

Swelling was determined by comparing the change in volume (the difference between the initial oven-dry condition (V_3) and the condition after immersion in water (V_2)), using Equation (6):

$$Swelling\ (\%) = (V_2 - V_3)\ /\ V_3 \times 100 \qquad (6)$$

For calculating shrinkage, specimens that had been immersed in water were placed in the oven until reaching oven-dry condition again. The subsequent oven-dry volumes were then determined (V_4), and the volume shrinkage was calculated as shown in Equation (7):

$$Shrinkage\ (\%) = (V_4 - V_2)\ /\ V_2 \times 100 \qquad (7)$$

Anti-swell efficiency (ASwE) was determined by finding the difference between swelling of the untreated wood (sw_1) and that of furfurylated wood (sw_2) and comparing it to sw_1. Anti-shrink efficiency (AShE) was based on a comparison between the difference between the shrinkage of untreated wood (sh_1) and that of furfurylated wood (sh_2) and comparing it to sh_1. The two characteristics were calculated as shown in Equa-

tions (8) and (9):

$$ASwE\ (\%) = (sw_1 - sw_2)\ /\ sw_1 \times 100 \qquad (8)$$
$$AShE\ (\%) = (sh_1 - sh_2)\ /\ sh_1 \times 100 \qquad (9)$$

MOE and MOR were obtained by conducting bending tests with an Instron Universal Testing Machine (type 3369). Testing was done by placing a single-point load on the span of a sample, with 28 cm between the points of support of the test piece. Loading orientation was perpendicular to the tangential face of the test specimen, and a loading speed of 3.5 mm/min was used. The MOE and MOR were calculated using Equations (10) and (11):

$$MOE\ (kgf/cm^2) = (\triangle P\ L^3)\ /\ (4\triangle Y\ b\ h^3) \qquad (10)$$
$$MOR\ (kgf/cm^2) = (3P\ L)\ /\ (2b\ h^2) \qquad (11)$$

where $\triangle P$ is the difference between the upper and lower loading limits in the proportional limit region (kgf); $\triangle Y$ is the deflection (cm); P is maximum loading (kgf); L is span (cm); b is the width of the test specimen (cm); and h is the thickness of the specimen (cm).

Hardness was determined through the Janka test, which was done using a hemispherical steel ball with a diameter of 1.128 ± 0.005 cm in order to determine the required load until a depth of 0.564 cm was achieved on the surface of the test specimen. The loading orientation was perpendicular to the tangential face of the test specimen.

2.5. Data analysis

The effect of treatments on all properties was analyzed using a completely randomized block design, in which the block was wood species and wood furfurylation was the treatment. The data were analyzed with IBM SPSS version 22. Duncan's multiple range tests were performed for further analysis if the block factor

was significantly different ($p \leq 0.05$).

3. RESULTS and DISCUSSION

3.1. Wood discoloration

Fig. 1 shows the colors of the wood specimen. The color characteristics (L*, a*, and b*) and discoloration ($\triangle E$) of the wood specimens are shown in Table 2, and a summary of the analysis of variance (ANOVA) results is presented in Table 3.

From Table 2, it could be seen that the values of lightness (L*) of untreated wood were higher than furfuryl wood for all wood species, which indicated that the furfuryl wood had darker color than untreated wood. The values of a* and b* were also changed but the changes were not as big as the L* value.

According to the analysis presented in Table 3, the L* value was affected by wood species and furfurylation. As shown in Fig. 1, the untreated wood had a light color, with mangium being naturally darker than the other three wood species. The difference is reflected in the L* value of mangium (50.8) being much lower

Fig. 1. Color of untreated and furfurylated woods.

Table 2. Wood color characteristic (L*, a*, and b*) and discoloration of wood

Wood sp.	Treatment	L*	a*	b*	△E
Jabon	Untreated	82.4 (1.5)^d	1.6 (0.6)^a	24.2 (2.4)^c	58.1 (3.6)^c
	Furfurylated	26.2 (3.3)^a	3.6 (1.8)^{abc}	10.4 (4.5)^a	
Sengon	Untreated	81.2 (0.8)^{cd}	5.8 (0.8)^{cd}	18.2 (1.9)^b	56.1 (2.1)^{bc}
	Furfurylated	25.8 (2.1)^a	4.2 (1.6)^{bc}	11.0 (3.1)^a	
Mangium	Untreated	50.8 (3.9)^b	5.6 (0.9)^{cd}	26.4 (2.9)^c	32.9 (5.9)^a
	Furfurylated	24.2 (4.0)^a	2.4 (2.2)^{ab}	7.6 (3.5)^a	
Pine	Untreated	77.4 (3.8)^c	7.0 (1.0)^d	33.2 (2.6)^d	52.9 (3.7)^b
	Furfurylated	27.8 (4.4)^a	5.6 (3.3)^{cd}	15.6 (3.4)^b	

Values in parentheses are standard deviations.
$^{a-d}$ Values followed by the same letter within a columns are not statistically different based on Duncan's multiple range test.

Table 3. Summary of ANOVA results (F test) for discoloration

Response	Wood sp (A)	FA treatment (B)
L* value	**	**
a* value	**	**
b* value	**	**
Discoloration (△E)	**	**

** Highly significant difference ($p < 0.01$).
ANOVA: analysis of variance, FA: furfuryl alcohol.

than the other three wood species (77.4–82.4, with an average of 80.3). After the FA treatment, the lightness of the wood specimens was similar, with all of them becoming much darker. This change was indicated by the average L* values for untreated wood being 73.0 and those for furfurylated wood being 26.0 (range: 24.2–27.8); these values were significantly different from one another. However, furfurylated wood specimens, which all had a higher intensity of black color, were not significantly different from each other.

For the other colors, average a* values (green to red color) were 5.0 for untreated wood and 4.0 for furfurylated wood. The change in a* ranged from −2.0 to 3.2 points, indicating that furfurylated wood did not differ much from untreated wood. In the case of mangium, the a* value change was the highest at 3.2 points (5.6 to 2.4) and the color shifting toward green. For the b* value (blue to yellow), untreated wood was 25.2 and furfurylated wood 11.2 points; this change of 14.1 points was higher than that for a* but lower than that for L*. In summary, furfurylation caused the wood to become more blue (14.1 point reduction) and much more black (26.0 point reduction), but the color of green to red (a* value) changed very little (1.0 point reduction).

The color of all furfurylated wood specimens differed from that of control wood specimens, as indicated by all △E values being more than 12 points. Mangium had the smallest △E because the untreated wood of this species was already darker than that of the other species, but after furfurylation all wood had a similar dark color. Hadi *et al.* (2005) showed that the intensity of discoloration is affected by the WPG level of FA, with a higher WPG resulting in a greater discoloration toward a darker color. In other words, a lower discoloration value, especially the lightness, could be arranged with a lower level of WPG from FA treatment. This possibility was also suggested by Dong *et al.* (2016), who found that furfurylation could cause discoloration in all wood specimens, especially decreasing the L* value (i.e.,

becoming darker). In addition, the reported that the intensity of the discoloration depended on the polymer loading value.

3.2. Physical properties

Physical properties of the control and FA wood specimens, such as WPG, density, MC, water absorption, swelling, and shrinkage, are described for all four wood species and furfurylated wood in Table 4.

WPG indicated FA polymer loading into the wood. From Table 4, it could be mentioned that jabon had the lowest density and thus much more void space available for occupation by the polymer; consequently, it had the highest WPG. Although the density of sengon was only slightly higher than that of jabon, its WPG was much less because sengon wood has a waving or interlocking

grain, and the fresh cut timber had a smell of *Parkia* sp fruit (Martawijaya *et al.*, 1989). In addition, they informed that fiber length, fiber diameter, and lumen diameter were 1,979 μm, 54 μm, and 48 μm for jabon, and 1,242 μm, 46 μm, and 39 μm for sengon, respectively; number of pore, ray height, and ray width were 2−5 /mm², 580 μm, and 44 μm for jabon, and 1−3 /mm², 185 μm, and 16 μm for sengon, respectively. From these characteristics, it seems that jabon had more void for FA to enter than sengon.

Furthermore, sengon has the highest extractive content, with a soluble extraction rate of 19.6% in NaOH 1% compared with jabon (18.4%), pine (11.1%) (Martawijaya *et al.*, 1989), and mangium (16.3%) (Siagian *et al.*, 1999). In addition, Pari (1998) reported that sengon contained extractive substances, such as cellobiose, glucose, xylose, arabinose, ribose, oligosaccharide, penta-saccha-

Table 4. Physical properties of treated specimens of each wood species

Property	Treatment	Jabon	Sengon	Mangium	Pine
WPG (%)	FA wood	86.3 (6.0)^a	30.1 (3.7)^b	19.1 (4.8)^c	15.2 (4.9)^c
Density (g/cm³)	Untreated	0.34 (0.02)^a	0.36 (0.05)^a	0.60 (0.05)^c	0.72 (0.04)^d
	FA wood	0.64 (0.02)^c	0.46 (0.05)^b	0.73 (0.09)^d	0.83 (0.05)^e
Moisture content (%)	Untreated	12.61 (0.63)^e	11.46 (1.12)^d	11.03 (1.23)^e	9.69 (1.26)^d
	FA wood	2.11 (0.34)^a	2.65 (0.36)^{ab}	3.75 (0.44)^c	3.16 (0.34)^{bc}
Water absorption (%)	Untreated	66.9 (6.6)^f	41.2 (4.9)^e	32.3 (4.0)^d	27.5 (3.6)^c
	FA wood	5.85 (0.64)^a	6.57 (0.63)^a	7.63 (0.69)^{ab}	10.65 (1.02)^b
Swelling (%)	Untreated	8.01 (0.97)^d	8.01 (0.68)^d	11.08 (1.02)^f	9.75 (0.74)^e
	FA wood	1.38 (0.20)^a	2.38 (0.19)^b	2.63 (0.32)^b	4.21 (0.51)^c
Anti-swelling efficiency (%)	FA wood	82.7 (2.7)	70.0 (4.4)	76.2 (2.1)	56.7 (5.3)
Shrinkage (%)	Untreated	6.89 (0.42)^e	3.18 (0.36)^c	4.15 (0.59)^d	10.40 (1.16)^f
	FA wood	1.40 (0.27)^a	1.39 (0.23)^a	1.96 (0.20)^b	3.69 (0.60)^d
Anti-shrinkage efficiency (%)	FA wood	79.6 (4.1)	55.9 (8.7)	52.0 (6.6)	63.9 (8.3)

Values in parentheses are standard deviations.
$^{a-f}$Values followed by the same letter within a row are not statistically different based on Duncan's multiple range test.
WPG: weight percent gain, FA: furfuryl alcohol.

ride, long-chain fatty-acids such as capriate acid, myristic acid, myristoleic acid, pentadecylic acid, palmitic acid, margaric acid, stearic acid, oleic acid, linoleic acid, and arachidonic acid. The extractive content of sengon likely hindered the FA monomer from entering the void space of the wood. Mangium and pine had much lower WPG values because these wood species have a much higher density than the other two wood species. Their thicker cell walls and less void space meant that less FA could penetrate into the wood.

According to the ANOVA results presented in Table 5, wood species had a significant effect on polymer loading. Jabon wood had the highest WPG, which was significantly different from that of sengon. Mangium and pine were not different from each other, but both differed from the other two species. WPG of pine only reached 15%, which was lower than the WPG reported by Esteves *et al.* (2011). They treated sapwood of *Pinus pinaster* with a 70% FA mixture and obtained a WPG of 38%. Wood species and catalyst could explain the WPG difference. Rahman *et al.* (2017) suggested that a 50:50 ratio of FA to 2-ethylhexyl methacrylate was the most suitable for impregnation of FA into wood.

At air-dry condition, the densities of untreated jabon

and sengon were low (0.34 and 0.36 g/cm^3, respectively), while those of untreated mangium and pine were medium (0.60 and 0.72 g/cm^3, respectively). The density of wood specimens affected their physical and mechanical properties. The furfurylated wood specimens had a higher density than the untreated specimens, and the increment of the density of the specimens was proportional to the WPG value. As shown by the ANOVA results in Table 5, wood species and FA treatment affected wood density. Further statistical analysis showed that the density of furfurylated wood was significantly higher than that of untreated wood for all species.

The ANOVA results in Table 5 also show that the MC of wood was affected by treatment and wood species. The MC of furfurylated wood was 74% lower than that of untreated wood, and this decrease was much greater than the results reported by Esteves *et al.* (2011). They found that the average WPG of *P. pinaster* was 38% and the equilibrium MC decreased by more than 40%. The presence of FA polymers in the wood could reduce its MC because they occupy the void space in the wood; in addition, FA polymers could bind to cell wall molecules (Gérardin, 2016).

With regard to wood species and MC of untreated wood, higher-density wood specimens tended to have a lower MC. This was likely because the wood had thicker cell walls, which prevented water from reaching the inner parts. In contrast, wood with a lower density has thinner cell walls, which would allow water to more easily enter all parts of the cell wall. In the case of furfurylated wood, the opposite occurred. Higher-density wood that was furfurylated tended to have a higher MC because the inner cell wall components did not easily bind with FA. The higher density meant that the FA monomer had difficulty reaching the inner cell wall components. However, in the lower-density wood, the FA monomer could easily reach more cell wall components. Consequently, the cell wall became more hydrophobic due to FA filling the void space and binding to

Table 5. ANOVA results (*F* test) for physical properties

Property	Wood species	FA treatment
Polymer loading (%)	**	**
Density (g/cm^3)	**	**
Moisture content (%)	**	**
Water absorption (%)	**	**
Swelling (%)	**	**
Anti-swelling efficiency	**	**
Shrinkage (%)	**	**
Anti-shrinkage efficiency	**	**

** Highly significant difference ($p < 0.01$).
ANOVA: analysis of variance, FA: furfuryl alcohol.

cell wall components (Gérardin, 2016).

Based on the ANOVA results in Table 5, treatment and wood species affected water absorption of the wood. The average water absorption of untreated wood was 42.0% and that of furfurylated wood was only 7.7%, representing an 82% decrease compared with untreated wood. This finding was similar to that of Morozovs *et al.* (2018), who reported that wood furfurylation decreased water absorption by 80% compared with untreated wood.

Furfurylated wood had FA polymer in the void space, resulting in less space for free water. It also had fewer available hydroxyl groups in the cell wall components, which meant less water could be held via hydrogen bonds by the cell wall. Both factors could result in water absorption of furfurylated wood being much less than that of untreated wood. Regarding wood species, untreated wood with a higher density tended to have a lower water absorption value probably because the void space was much smaller and the cell wall was much thicker than wood with lower density. Consequently, the wood with a higher density would have had less free water able to occupy the void. Further analysis with Duncan's multiple range test (Table 4) showed that samples of all four untreated wood species had significantly different water absorption values, with the lowest-density wood (jabon) waving the highest average water absorption value and the highest-density wood (pine) having the lowest.

Based on the ANOVA results in Table 5, FA treatment and wood species significantly affected wood swelling and shrinkage. Swelling and shrinkage values of furfurylated wood were much lower than those of untreated wood, which was indicated by the anti-swell efficiency reaching a range of 56.7% to 82.7% (average: 69%) and AShE reaching 52.0% to 79.6% (average: 62%). The FA treatment improved the dimensional stability of the wood, and this finding was in line with Li *et al.* (2015), who reported that furfurylation signifi-

cantly improved the dimensional stability and durability of pine wood. Morozovs *et al.* (2018) found that wood furfurylation decreased swelling by 40% during cyclic hydrothermal treatment compared with untreated wood. Furfurylated wood would have less swelling and shrinkage because the void space is filled with FA polymer. Further, hydroxyl groups in the cell wall would react with FA, yielding a more hydrophobic cell wall.

3.3. Mechanical properties

Mechanical properties, such as MOE, MOR, strength class, side hardness, and end hardness of untreated and furfurylated wood specimens, are described in Table 6 for the four wood species. Results of the ANOVA for each property are described in Table 7.

According to the results in Table 7, MOE was significantly affected by wood species and FA treatment factors. Jabon and sengon had lower MOE because they had lower density compared to the other. Pine had the highest MOE regarding to having highest density, and this matter was in-line with Epmeier *et al.* (2004) and Mardikanto *et al.* (2011).

In terms of FA treatment, the average MOE increment reached 14%, and the results are similar to those of Jia and Fiedler (2018). They reported that FA pretreatment is a promising method for improving the mechanical properties of flax fiber composites (e.g. Young's modulus increases up to 18%). Further analysis with Duncan's multiple range test showed that FA treatment did not significantly affect the MOE of jabon and pine wood, but it did increase the MOE of sengon and mangium specimens. The MOE improvement in sengon and mangium was in line with findings from Dong *et al.* (2015), who used fast-growing poplar (*Populus* sp.) in their research. The MOE increments of furfurylated wood compared with untreated wood differed for each species, and it appeared that wood density affected the parabolic to MOE increment.

Table 6. Mechanical properties of wood specimens

Property	Treatment	Jabon	Sengon	Mangium	Pine
MOE (1,000 kgf/cm^2)	Untreated	52.7 (4.4)[a]	54.2 (7.1)[a]	73.7 (5.5)[c]	106.4 (12.0)[d]
	FA wood	54.1 (3.9)[a]	65.0 (6.3)[b]	101.6 (8.1)[d]	106.6 (8.3)[d]
	Average	53.4	59.6	87.7	106.5
MOR (kgf/cm^2)	Untreated	495 (26)[b]	455 (39)[b]	665 (63)[c]	979 (105)[e]
	FA wood	316 (34)[a]	459 (43)[b]	1,052 (81)[f]	847 (55)[d]
	Average	405.5	457.0	858.5	913.0
Strength class	Untreated	IV	IV	III	II
	FA wood	IV	IV	II	II
Hardness (kgf/cm^2)	Untreated	128 (10)[a]	135 (19)[a]	259 (30)[c]	433 (39)[d]
	FA wood	262 (36)[c]	188 (17)[b]	478 (35)[e]	447 (40)[d]
	Average	195.0	161.5	368.5	440.0

Values in parentheses are standard deviations.
[a-f]Values followed by the same letter within a row are not statistically different based on Duncan's multiple range test.
MOE: modulus of elasticity, FA: furfuryl alcohol, MOR: modulus of rupture.

Table 7. ANOVA results (*F*-test) for mechanical properties

Response	Wood species (A)	FA Treatment (B)
MOE (1,000 kgf/cm^2)	**	**
MOR (kgf/cm^2)	**	ns
Hardness (kgf/cm^2)	**	**

** Highly significant difference ($p < 0.01$); ns, nonsignificant difference.
ANOVA: analysis of variance, FA: furfuryl alcohol, MOE: modulus of elasticity, MOR: modulus of rupture.

The MOR was affected by wood species, but it was not affected by the FA treatment. Jabon and sengon had lower MOR because they had lower density compared to mangium and pine. Pine had the highest MOR regarding to having highest density among them, and this matter was in-line with Mardikanto *et al.* (2011).

Regarding to FA treatment, the MOR values of untreated sengon and FA sengon did not differ, but those for the other species did. For jabon and pine, the value decreased, but it increased for mangium. Using poplar wood, Dong *et al.* (2015) also showed that the MOR of furfurylated wood decreased compared with untreated wood. With regard to the strength class, furfurylated mangium only increased one class compared with untreated wood. Even though the MOR values decreased for the other wood species, the strength class did not decrease or was in the same class as untreated wood.

Wood hardness was significantly affected by wood species and FA treatment factors. Jabon and sengon had lower hardness because they had lower density compared to mangium and pine. Pine had the highest hardness regarding to having highest density among them, and this matter was in-line with Epmeier *et al.* (2004) and Mardikanto *et al.* (2011). In terms of FA treatment, the hardness of furfurylated wood increased by 44%, and this result was similar to that of Esteves *et al.* (2011), who found that the hardness of furfurylated wood increased by about 50%. With regard to the further data analysis of Duncan's multiple range test, the hardness of

furfurylated jabon, sengon, and mangium specimens was higher than that of the untreated specimens; however, the values were not different for pine. In general, furfurylation of wood increased its hardness, and this result was in line with Dong *et al.* (2015), who reported that furfurylated poplar wood had improved hardness.

4. CONCLUSION

The wood densities of untreated jabon, sengon, mangium, and pine were lower than furfurylated wood and the WPG of the specimens after the impregnation process reached 86.3%, 30.1%, 19.1%, and 15.2%, respectively. The four furfurylated tropical wood species had different and darker colors that were more blue and black. On average, they had 74% decreased MC, 82% decreased water absorption, and much higher dimensional stability, as indicated by an anti-swell efficiency of 69% and an AShE of 62% compared with untreated wood. The mechanical properties of furfurylated wood were enhanced in MOE (increased 14%) and hardness (increased 44%).

CONFLICT of INTEREST

No potential conflict of interest relevant to this article was reported.

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