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Color Change and Physical-Mechanical Properties of Polystyrene-Impregnated Glulam from Three Tropical Fast-Growing Wood Species

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Abstract: The aims of this work were to determine the color change and physical–mechanical properties of polystyrene glulam from three tropical wood species. Wood laminas were cut from logs harvested from a young plantation forest of manii (*Maesopsis eminii*), mangium (*Acacia mangium*), and rubber-wood (*Hevea brasiliensis*). The laminas were impregnated with monomer styrene that was polymerized using potassium peroxy-disulfate as a catalyst and heat. Three-layer glulam was constructed from the polystyrene laminas, using isocyanate glue and cold press. For comparison purposes, three-layer untreated glulam and solid wood samples were prepared. The results showed that the color change of polystyrene glulam was very small compared with untreated glulam. Polystyrene glulam had the highest density, while the density of untreated glulam did not differ from that of the solid wood. The moisture content of all products was matched to the environment, and fulfilled the Japanese standard. Compared with both types of glulams, solid wood had lower values for modulus of rupture (MOR), modulus of elasticity (MOE), and hardness, but higher shear strength. Meanwhile, polystyrene glulam had lower values for MOR and MOE, equal shear strength and wood failure, and higher hardness than the untreated glulam. All glulams had very little delamination in the hot water test. Only rubber-wood glulams fulfilled JAS 234-2003 for MOR, MOE, shear strength, and delamination. To obtain adequate physical–mechanical properties of glulams, medium-density wood is recommended for glulam manufacturing.

Keywords: color change; glulam properties; polystyrene glulam; tropical wood

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1. Introduction

In Indonesia, the supply of logs to the wood industry reached 58 million m^3 in 2019, and about 85% of the supply was from plantation forests [1]. Logs from plantation forests are mostly cut from young trees that are less than 10 years old. Timber is produced from small-diameter logs, which predominantly contain sapwood and have a high juvenile wood content. As a result, the physical–mechanical properties are inferior to those of mature wood [2]. To obtain larger-dimension timber with better physical–mechanical properties from plantation forest wood, the manufacture of glued laminated timber (glulam) has been developed.

Glulam is manufactured with sheets of thin-cut lumber, or laminas, that are glued together with good-quality adhesive. For better results, the laminas can be arranged so that a stronger lamina is used in the outer layers, with weaker ones in the inner layers [3]. In addition, Komariah et al. [3] reported that three- and five-layer mangium (*Acacia mangium*) glulams using isocyanate glue could fulfill the Japanese Agricultural Standard (JAS) 234-

2003 [4] requirements for decorative structural glulam outlined for sugi (*Cryptomeria japonica*) wood.

Other researchers found that the density and shear strength of glulams constructed from pine (*Pinus merkusii*), jabon (*Anthocephalus cadamba*), and sengon (*Falcataria moluccana*) with mahogany (*Swietenia* sp.) tannin adhesive were not different from those of solid wood. Since it has a high density, pine glulam could fulfill the modulus of rupture (MOR) and modulus of elasticity (MOE) requirements of JAS 234-2003 [5]. In another study, Lestari et al. [6] made glulam from pine and jabon wood and isocyanate glue, and the results showed that the mechanical properties of the glulam in terms of MOE, MOR, and shear strength were higher than those of solid wood from each species; however, the glulam matched the JAS 234-2003 requirements for MOR and shear strength only.

To produce a higher-density product with better physical–mechanical properties, monomer styrene can be impregnated into wood and then polymerized with a chemical catalyst and heat. Stolf and Lahr [7] showed that polystyrene-impregnated *Pinus caribaea* wood had enhanced physical–mechanical properties compared with untreated wood. In another study, polystyrene-impregnated fir (*Abies* sp.) and aspen (*Populus* sp.) had better properties than untreated wood in terms of MOR, MOE, and hardness, as well as higher density [8].

Some research on tropical woods has shown that polystyrene impregnation of pine (*P. merkusii*), rubber-wood (*Hevea brasiliensis*), and sengon increased MOR, MOE, and hardness [9]. Polystyrene impregnation of randu (*Ceiba pentandra*) and angsana (*Pterocarpus indicus*) wood enhanced the density, dimensional stability, hardness, MOE, MOR, and compression parallel to the grain [10]. In another research study, polystyrene impregnation of five types of Indonesian wood, including sengon, manii (*Maesopsis eminii*), pine (*P. merkusii*), duabanga (*Duabanga moluccana*), and maniani (*Flindersia pimenteliana*), were shown to improve the physical-mechanical properties of the wood [11]. Polystyrene impregnation of kecapi (*Sandoricum koetjape*) and durian (*Durio zibethinus*) improved the physical–mechanical properties of both types of wood and yielded better insulator properties compared with untreated wood [12].

Polystyrene can also be used as a wood adhesive. Liptáková et al. [13] reported that the adhesion of polystyrene to wood was due to the effect of dispersion forces (60%) and polar forces (40%). It was also possible to use polystyrene in bonding veneers, with low-pressure preheating being a necessary step to obtain better final shear strength of the wood–thermoplastic joints [14]. In another research study, polystyrene was used as the adhesive in manufacturing laminated veneer lumber that had suitable mechanical properties comparable to those of lumber made using thermosetting resins. However, increasing the amount of polystyrene reduced both the density and the mechanical properties of the finished product [15].

Treatment with certain chemical compounds can change the wood color. Discoloration of four tropical wood species occurred after furfurylation, with treated wood samples being darker in color than untreated wood [16]. For mangium and sengon wood samples that were exposed to smoke produced from the pyrolysis of salam (*Syzygium polyanthum*) wood, the wood color was different from that of untreated wood and the discoloration of sengon was greater than for mangium [17]. For ThermoWood, after thermal modification the wood became less bright, but had more red and yellow colors [18].

The above results show that small-diameter logs can be used to manufacture glulam with larger dimensions and better physical–mechanical properties than untreated timber. Polystyrene impregnation can also enhance the physical–mechanical properties of wood. The possibility exists that small-diameter logs can be manufactured into glulam using polystyrene-impregnated laminas to obtained better physical–mechanical properties. Regarding to the previous research studies, the polystyrene-impregnated laminas would have better physical–mechanical properties, and if the laminas were manufactured for glulam, it could be assumed that the glulam would also have better physical–mechanical properties. On the other matters, the color of polystyrene was transparent, and we assumed that the

impregnation of polystyrene to laminas would result in no change of the color of the laminas. The aims of this work were to determine the color changes and physical–mechanical properties of polystyrene glulam constructed from three tropical wood species, including manii, mangium, and rubber-wood.

2. Materials and Methods

2.1. Materials

Logs of manii (*Maesopsis eminii*), mangium (*Acacia mangium*), and rubber-wood (*Hevea brasiliensis*) with a diameter less than 20 cm were harvested from a plantation forest that was less than ten years old in Bogor, Indonesia, with coordinate of 6.463° to 6.519° SL and 106.419° to 106.477° EL. The micro-climate in 2020 of that area in terms of average temperature was 26.4 ± 0.8 °C, relative humidity of 83.7 ± 5.6%, solar radiation of 5.2 ± 3.0 h/d, and rain fall of 4082 mm/y, and this area is classified to A type of rainfall regarding the Schmidt–Ferguson classification [19].

The logs were cut into flat-sawn laminas with a size of 1.7 cm by 6 cm by 50 or 80 cm in thickness, width, and length, respectively. The 50-cm length of laminas were prepared for the density, moisture content (MC), shear strength, hardness, and delamination tests of glulam, while the 80-cm laminas were for modulus of elasticity (MOE) and modulus of rupture (MOR) tests of glulam. After cutting, the laminas were kiln-dried to reach about 12% moisture content (MC). The MOE of each lamina was estimated using a nondestructive testing system with a wood-grading machine (Panter MPK-5) [20]. The laminas were then classified according to their MOE values. The laminas with higher MOE values were used for outer layers in three-layer glulam manufacturing, while those with lower values were used for the inner layer. Both untreated lamina and polystyrene-impregnated lamina were prepared and used to create untreated glulam (control) and polystyrene glulam.

The laminas were weighed and then vacuumed at 0.80 bars for 30 min in a tank. For the impregnation process, potassium peroxy-disulfate was added as a catalyst to monomer styrene (0.01:1 v/v), and the solution was introduced into the tank as the vacuum was released. Afterward, a pressure of 9.81 bars was applied for another 30 min. After the impregnation process, each lamina was wrapped with aluminum foil (to prevent the polystyrene solution to come out during the polymerization process; this did not make the apparatus dirty), and placed in an oven at 60 °C for 24 h [9,11]. The foil was then removed, and each lamina specimen was weighed to calculate the weight percent gain (WPG). The WPG was determined through weighing the wood specimen before treatment at oven dried condition (W1), and then the oven dried weight of specimen was also determined after impregnation with polystyrene (W2). The WPG was calculated using the following Equation (1):

$$\text{WPG (\%)} = (\text{W2} - \text{W1})/\text{W1} \times 100 \quad (1)$$

Conditioning of the specimens was conducted at room temperature for 2 weeks. In addition, a Scanning Electron Microscope (SEM, Zeiss–Evo 50) was used to determine the morphology prior and after impregnation of manii wood with polystyrene. The specimens were extracted from laminas with the dimension of 5 mm × 5 mm (cross section) and 5-mm longitudinal direction.

Three-layer glulam was manufactured by using the laminas with a higher MOE in the face and back layers, while the lamina with the lower MOE was used for the core layer. The laminas were places with a longitudinal fiber orientation along the length of the glulam. Isocyanate glue was spread at 280 g/m^2 in a single glue line [3], and the laminas were then cold-pressed with a specific pressure of 0.98 MPa for 3 h, followed by conditioning at room temperature for 2 weeks in the Forest Products Research and Development Centre, Bogor, Indonesia. A water-based polymer isocyanate adhesive was provided by PT Polychemie Asia Pacific Permai, Jakarta, Indonesia. The resin (PI–127 T) was a milky white viscous liquid with solid content of 40–44%, viscosity at 23 °C was 5,000–15,000 cps, and pH was 6.5–8.5. For the hardener (H–3M), the appearance was dark brown, viscous liquid (viscosity at 23 °C) was 150–250 cps, and solid content was 98%.

For comparison purposes, solid wood samples were also prepared. Six replications of the test specimens were manufactured for each treatment combination of wood species and wood product.

2.2. Discoloration of Polystyrene Glulam

The colors of the untreated glulam and polystyrene glulam were determined according to the CIELab method of measuring L* (lightness), a* (red to green), and b* (blue to yellow) values [21], using a scanner machine (CanoScan 4400F) and the Adobe Photoshop CS5 application. The color change of wood specimens was calculated by referring to CIELab, while classification was according to Hunter Lab [22] and Hrčková et al. [23].

2.3. Physical and Mechanical Tests

Physical–mechanical properties, including density, MC, MOE, MOR, shear strength, hardness, and delamination in hot water, were measured according to the Japanese Agricultural Standard (JAS) 234-2003 [4].

2.3.1. Density and MC

The specimen for density and MC was 5 cm × 5 cm × 5 cm in length, width, and thickness, respectively. The density of specimen was determined through measuring the volume of specimen at air dry condition (V1, m^3), and oven dry weight (W1, kg), and the wood density was calculated by the following Equation (2):

$$\text{Wood density } (kg/m^3) = W1/V1 \quad (2)$$

Moisture content (MC) was determined with the oven dry weight method. The air dry specimen was weighed as initial weight (W2, kg), and then put in the oven at a temperature of 103 ± 2 °C until constant weight as oven dry weight (W1, kg). The MC was calculated by the following Equation (3):

$$\text{MC } (\%) = (W2 - W1)/W1 \times 100 \quad (3)$$

2.3.2. MOE and MOR Tests

MOE and MOR were obtained with bending tests using a Shimadzu Universal Testing Machine (UH-100A Series). Testing was done through a single point load on the span of a sample with a distance of 70 cm between the points of support of the test piece. The loading orientation was perpendicular to the tangential face of the solid wood and the lamina face of the glulam test specimens, with a loading speed of 3.5 mm/min. The MOE and MOR were calculated by the following Equations (4) and (5).

$$\text{MOE } (kg/cm^2 \text{ converted to GPa}) = (\Delta P \times L^3)/(4 \times \Delta Y \times b \times h^3) \quad (4)$$

$$\text{MOR } (kg/cm^2 \text{ converted to MPa}) = (3 \times P \times L)/(2 \times b \times h^2) \quad (5)$$

where ΔP is the difference between the upper and lower loading limits in the proportional limit region (kg), ΔY is the deflection with respect to ΔP (cm), L is span (cm), b is the width of the glulam (cm), h is the thickness of the glulam (cm), and P is the maximum loading (kg).

The strength class of Indonesian wood was class I to V, from the strongest to the weakest woods, respectively, as shown in Table 1 [24].

Table 1. Strength classification of Indonesian wood.

Strength Class	Specific Gravity	MOR (MPa)
I	>0.90	>107.9
II	0.60–0.90	71.1–107.9
III	0.40–0.60	49.0–71.1
IV	0.30–0.40	35.3–49.0
V	<0.30	<35.3

2.3.3. Shear Strength

The shear strength of glue line parallel to the grain direction was determined. The two glue lines of the three laminations were tested. The specimen for shear strength was 5 cm × 5 cm × 5 cm in length, width, and thickness, respectively. The shear strength was calculated as follows (Equation (6)):

$$\text{Shear strength (kg/cm}^2\text{ converted to MPa)} = \text{Rupture load (kg)/Area of bonding layer (cm}^2\text{)} \quad (6)$$

2.3.4. Hardness

The specimen for hardness was 5 cm × 5 cm × 5 cm in length, width, and thickness, respectively, according to American Standard Testing and Materials ASTM D 143-94 [25]. Hardness was determined through the Janka test which was done using a 1.128 ± 0.005-cm diameter of hemispherical steel ball in order to determine the required load until the ball had penetrated to one half its diameter or 0.564 cm upon test specimen surface, as determined by the tightening of the collar against the specimen. The projected area of the ball on the test specimen was 1 cm^2. Side hardness was determined if the loading orientation was perpendicular to tangential face of the test specimen. The hardness was calculated by the following Equation (7):

$$\text{Hardness (kg/cm}^2\text{ converted to MPa)} = \text{(Load required of Hemispherical steel ball penetrated to the wood (kg))/(Area of hemispherical steel ball (cm}^2\text{))} \quad (7)$$

2.3.5. Delamination in hot water

The hot water delamination test was carried out by soaking test specimens by boiling the test specimen in water (100 °C) for 4 h, then soaking it in water at room temperature for 1 h before placing it in an oven at 70 ± 3 °C for 18 h. The specimen for delamination was 5 cm × 5 cm × 5 cm in length, width, and thickness, respectively. The delaminating ratio was calculated by the following Equation (8):

$$\text{Delamination ratio (\%)} = \text{((Sum of delaminated lengths of two cross-sections)/(Sum of gluing lengths of two cross-sections))} \times 100 \quad (8)$$

2.4. Analysis of the Data

The data were analyzed in a completely randomized block design using two factors, wood species and wood product. The wood species as a block factor consisted of three levels, namely manii, mangium, and rubber-wood, while the factor of the wood product also consisted of three levels, namely solid wood, untreated glulam, and polystyrene glulam. Duncan's multi-range test was done for further analysis when the main factor was significantly different at $p \leq 0.05$.

3. Results and Discussion

3.1. Discoloration of Polystyrene Glulam

The test specimens of each wood species and wood product are shown in Figure 1. The color characteristics are presented in a histogram of L*, a*, and b* values of untreated and polystyrene glulam in Figure 2.

Figure 1. Test specimens of each wood species and wood product.

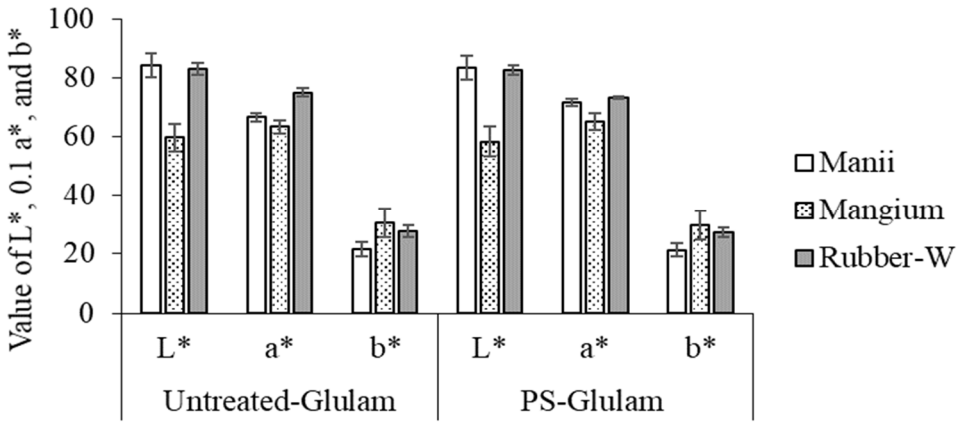


Figure 2. Values of L*, a*, and b* of the glulam. PS = polystyrene.

The lowest L* value belonged to mangium wood, indicating that the wood had a darker color than others. Rubber-wood had the highest a* value, which indicated that it had more red compared with the other woods. Manii had more blue than the other woods, as indicated by it having the lowest b* value. Nevertheless, according to the t-test, the color characteristics of each wood and wood product were not statistically different. After impregnation with polystyrene, the color change (ΔE) of manii, mangium, and rubber-wood was 1.6, 1.9, and 1.8, respectively, and according to Hunter Lab [22], these values indicated a very small color change (ΔE < 2.0). The color change of polystyrene glulam was in line with the findings reported by Nurhanifah et al. [26], who made sengon polystyrene glulam. The small color changes were explained by polystyrene being transparent and not having any effect on changing the color.

3.2. Physical Properties

The density and MC of solid wood, untreated glulam, and polystyrene glulam of each wood species are shown in Figure 3. The results of the analysis of variance of physical

properties are presented in Table 2, and further analysis from Duncan's multi-range test is described in Table 3.

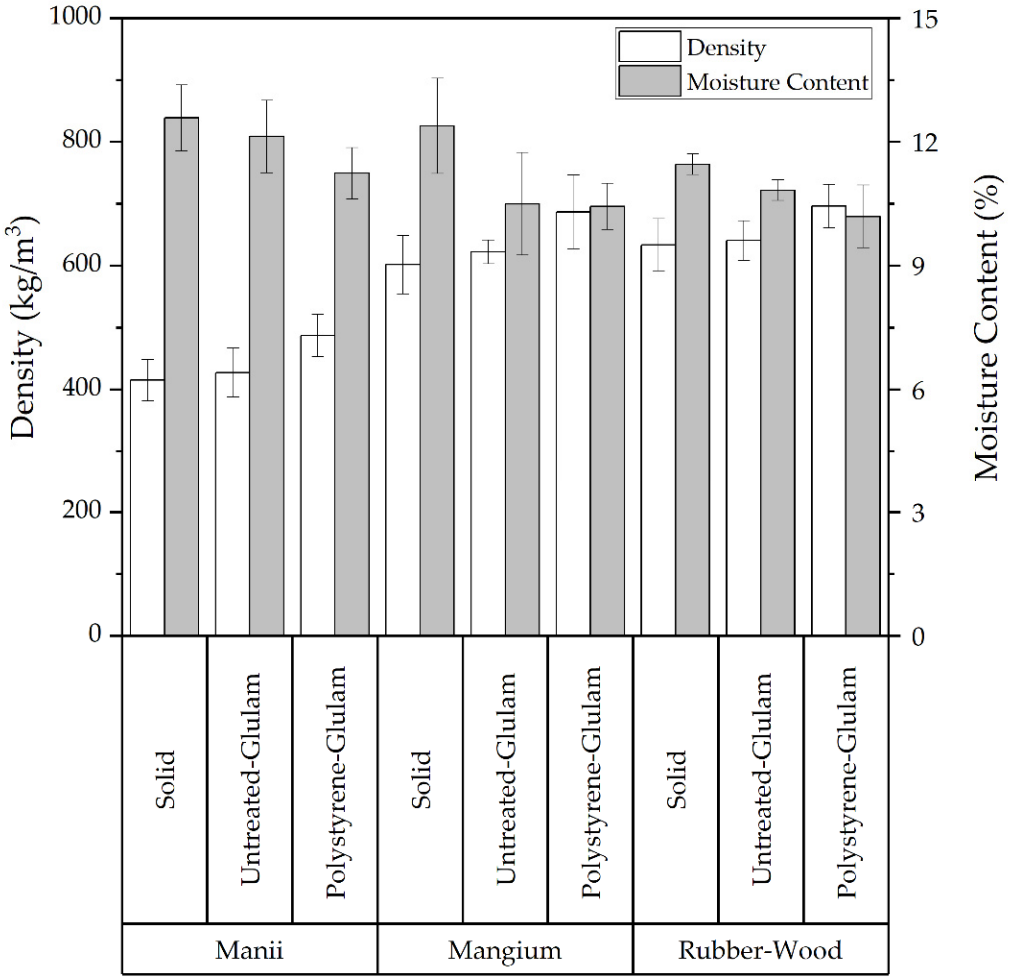


Figure 3. Density and moisture content of each wood species and wood product.

Table 2. Variance analysis summary of physical properties.

Parameter	Density	Weight % Gain	Moisture Content
Wood species	**	**	**
Wood product	**	na	**

na, not available. ** Highly significance difference ($p \leq 0.01$).

Table 3. Duncan's multi-range test of physical properties.

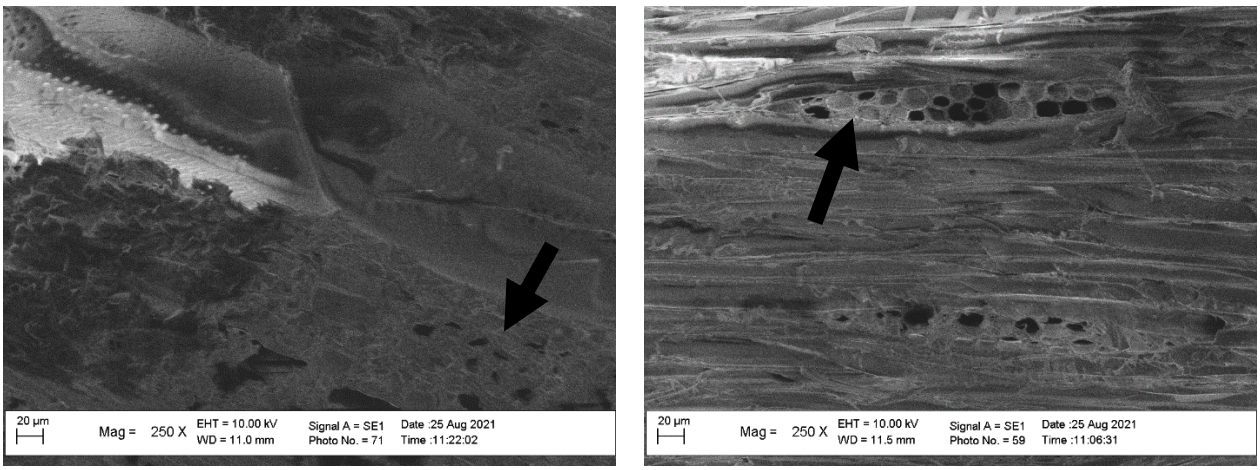
Parameter	Wood Species			Wood Product		
	Manii	Mangium	Rubber-Wood	Solid Wood	Untreated Glulam	Polystyrene Glulam
Density	439 a	637 b	656 b	550 c	562 c	625 d
Weight % gain	16.9 a	16.1 a	12.3 b	na	na	na
Moisture content	12.0 a	11.1 b	10.8 b	12.1 c	11.2 d	10.6 d

na, not available. Values with the same letter within a row are not significantly different.

Based on the results presented in Table 2, wood species and wood products had a highly significant effect on sample density. Manii, a low-density wood, had the lowest density. It was different from the other two wood species, which were not different from each other; mangium and rubber-wood are both considered to be medium-density wood [27]. As shown in Table 3, the densities of solid wood and untreated glulam were

not different, which indicated that the glue line and the pressing process did not affect the density of untreated glulam. Furthermore, both densities were significantly different from polystyrene glulam, which had the highest density. The increased density of polystyrene glulam compared with the other samples could be due to each lamina being impregnated with polystyrene prior to the manufacture of the glulam. The impregnation caused the lamina to have a certain amount of polymer loading and weight percent gain. The density increment of polystyrene glulam reached 10.7% compared with untreated glulam.

Based on the results of SEM (Figure 4), the surface morphology of polystyrene impregnated manii wood had shown that some pores were occupied by polystyrene (Figure 4b) while the pores in the untreated wood were still empty (Figure 4a). This result was similar to the findings by Stolf and Lahr [7], who reported that polystyrene penetrated and subsequently polymerized inside the wood anatomical structure.



(**a**) (**b**)

Figure 4. Scanning electron microscopy of (**a**) untreated and (**b**) polystyrene-impregnated manii wood. Remarks: The arrows indicate the voids.

Polymer loading is expressed as the weight percent gain for manii, mangium, and rubber-wood: 16.9 ± 2.9%, 16.1 ± 1.8%, and 12.3 ± 2.3%, respectively. Budiman et al. [11] impregnated polystyrene into manii wood with the density of 370 kg/m^3 and obtained a polymer loading of 6.2%, which was 63% lower than our result. In contrast, Hadjib [9] used rubber-wood with a density of 510 kg/m^3 and got polymer loading of 26.9%, or more than twice our result. As shown in Table 1, wood species had a highly significant effect on weight percent gain due to polystyrene impregnation. Rubber-wood had the lowest weight percent gain because it had the highest wood density. The higher density wood had smaller voids that could be filled by the polystyrene. This result was in line with the findings of other researchers who reported that wood with a higher density had a lower weight percent gain of polystyrene polymer loading [9].

Table 2 shows that wood species and product type had a highly significant effect on MC. The MC values were similar to each other, and all test specimens had an MC similar to the ambient moisture content in Bogor, in the range of 10%–18% [28]. The MC of polystyrene glulam was the lowest because polystyrene is a hydrophobic agent that can reduce the moisture adsorbed to the glulam. The MC of polystyrene glulam decreased by 0.6% compared with the untreated glulam. Furthermore, the MC of all glulams fulfilled the JAS 234-2003 standard, which requires a maximum MC of 15%.

3.3. Mechanical Properties

Strength-tested specimens of rubber-wood polystyrene glulam are shown in Figure 5, mechanical properties of each wood species and wood product are presented in Table 4, a summary of the analysis of variance is presented in Table 5, and the results of the Duncan's

multi-range test are shown in Table 6. According to Table 5, the MOR was affected by wood species and wood product factors. Manii had the lowest MOR, given that it had the lowest density, and the other two wood species had higher values for MOR and density. These findings were in accordance with the report by Viet et al. [29], who noted that acacia wood, which has a higher density than other wood species, had a higher MOR. Mangium had a higher MOR than rubber-wood because some of the wood had heart-wood, but rubber-wood dominantly consists of sapwood, and consequently, mangium had a higher MOR than rubber-wood.

Figure 5. Strength-tested specimens of polystyrene-impregnated rubber-wood glulam.

Table 4. Mechanical properties of each wood species and wood product.

Wood Species	Wood Product [1]	MOR (MPa)	Strength Class [2]	MOE (GPa)	Shear Strength (MPa)	Wood Failure (%)	Hardness (MPa)
Manii	Solid wood	42.7 (3.3)	IV	4.5 (0.4)	6.2 (1.1)	-	22.8 (2.4)
	Untreated glulam	61.7 (4.9)	III	6.8 (0.4)	4.3 (0.5)	73 (31)	25.6 (2.2)
	PS Glulam	48.6 (3.2)	IV	5.7 (0.5)	3.9 (0.5)	48 (34)	32.2 (3.3)
Mangium	Solid wood	79.4 (8.4)	II	10.5 (1.5)	5.1 (1.2)	-	49.8 (5.6)
	Untreated glulam	102.1 (9.0)	II	12.1 (1.1)	4.9 (2.2)	28 (26)	64.0 (6.2)
	PS Glulam	81.6 (7.6)	II	11.3 (0.6)	4.7 (1.6)	13 (5)	66.3 (3.6)
Rubber-wood	Solid wood	50.5 (8.6)	III	6.1 (0.6)	8.0 (1.1)	-	56.0 (4.4)
	Untreated glulam	72.7 (4.4)	II	8.3 (0.4)	6.8 (2.1)	25 (14)	57.1 (6.1)
	PS Glulam	64.9 (8.7)	III	7.5 (0.9)	6.2 (2.3)	55 (27)	64.9 (6.3)
JAS 234-2003		Min. 28.8		Min. 7.2	Min 5.2		

[1] PS = Polystyrene. [2] Strength class according to Indonesian standard [24].

Table 5. Summary of the analysis of variance of mechanical properties.

Parameter	MOR	MOE	Shear Strength	Wood Failure	Hardness	Delamination
Wood species	**	**	**	**	**	ns
Wood product	**	**	**	ns	**	ns

ns = not significantly different. ** Highly significant difference ($p \leq 0.01$).

Table 6. Duncan's multi-range test of mechanical properties.

Parameter	Wood Species			Wood Product		
	Manii	Mangium	Rubber-Wood	Solid Wood	Untreated Glulam	Polystyrene Glulam
MOR	51.0 a	87.8 b	62.7 c	57.6 d	78.8 f	65.0 e
Strength class	III	II	III	III	II	III
MOE	5.7 a	11.3 c	7.3 b	7.1 d	9.0 f	8.1 e
Shear strength	2.7 a	6.0 b	6.3 b	6.5 d	5.3 c	4.9 c
Wood failure	61 b	21 a	40 ab	-	40 c	39 c
Hardness	26.9 a	60.0 b	59.3 b	42.9 c	48.9 d	54.4 e

Values with the same letter in a row are not significantly different.

As shown in Table 6, the wood products differed, with solid wood having the smallest MOR. Untreated glulam and polystyrene glulam had a higher MOR than solid wood,

because the glulams were manufactured by placing laminas with the higher MOE in the face and back layers and the lamina with the lower MOE in the core layer. Use of the technique demonstrates that the lamina of the face layer could support a higher compression force and the back layer a higher tensile stress, with the assumption that the load was applied in the face layer.

According to Pelit and Emiroglu [8], the polystyrene-impregnated fir (*Abies bornmuelleriana*) and aspen (*Populus tremula*) wood had higher MOR values than untreated wood. Other studies indicated that polystyrene manii and rubber-wood had higher MOR values than solid wood [9,11]. Table 6 shows that polystyrene glulam had a 17.4% lower MOR compared with untreated glulam, despite polystyrene lamina having a higher MOR than untreated lamina. However, polystyrene glulam may have had a lower MOR than untreated glulam because the polystyrene on the lamina surface could interfere with the development of a proper glue-line, which would be a weak point in getting maximum strength. To obtain a better adhesion in polystyrene glulam, the hot press application for curing adhesive may provide better results. The MOR of manii polystyrene wood reported by Budiman et al. [11] was equal to that of manii polystyrene glulam in our study, and the development of manii polystyrene glulam could be considered more in the future.

Based on the strength class of Indonesian wood [24], solid woods of manii, mangium, and rubber-wood were in strength classes IV, II, and III, respectively. The untreated glulams of manii and rubber-wood were enhanced one class from the solid wood of the respective species, but even though the MOR of mangium increased, the untreated glulam remained in the same strength class as the solid wood. For the polystyrene glulam, the strength class of all wood products had the same class as each type of solid wood; even though they were different, the increment did not enhance the strength class. With regard to the JAS 234-2003 criteria, all wood products fulfilled the standard for MOR requirements.

The MOE was affected by the wood species and wood product factors. Manii had the lowest MOE, given that it had the lowest density wood, followed by rubber-wood and mangium, which had higher MOE values and densities. These findings were in line with the study by Viet et al. [29], who reported that acacia wood with a higher density had a higher MOE. The MOE of solid wood was the lowest value among wood products, followed by polystyrene glulam and untreated glulam. The MOE of polystyrene glulam was 9.8% lower than untreated glulam, likely because the polystyrene on lamina surfaces reduced their glue-ability and resulted in a weaker glue-line. With regard to the JAS 234-2003 standard, all wood products of mangium and both types of rubber-wood glulams fulfilled the MOE requirements.

Shear strength was affected by wood species and wood product factors. Rubber-wood, which had the highest density, had the highest shear strength. In terms of wood products, both types of glulam had a lower shear strength than solid wood; this finding indicated that the glue-line of glulam was weaker than the natural adhesion in the solid wood. Improvement of the glue-line could be attained by using hot press instead of cold press in the glulam manufacturing process. The shear strength of the two types of glulam was not significantly different, although polystyrene filled the wood anatomical structure (as shown in Figure 4), such as the vessels and tracheids, then caused the cell walls and other structures (such as ray) to become very dense [30]. In other words, polystyrene impregnated in the lamina was not a significant obstacle in producing lamina that was as good as the untreated glulam in terms of shear strength. The shear strength result was in line with the study by Nurhanifah et al. [26], who mentioned that untreated glulam was not significantly different from polystyrene glulam. All rubber-wood products had a shear strength of more than 5.2 MPa, and these rubber-wood products fulfilled the requirements of JAS 234-2003.

Wood failures were determined for glulams (untreated glulam and polystyrene glulam) only. The failure of solid wood is not reported because it had a 100% failure for all tested specimens. According to the analysis of variance, the wood failure was affected by wood species only. The highest wood failure (61%) was manii. Although it had a fairly

good adhesion quality, it was a low-density wood and had low strength. The shear strength of manii was the lowest value even though the glue line was fairly good. Rubber-wood and mangium had wood failures that were lower than that of manii. Both wood species had a higher density, and thus they had a higher shear strength than manii, because higher density wood can release force at a higher level. For untreated glulam and polystyrene glulam, wood failure did not differ, indicating a similar adhesion quality. In other words, polystyrene impregnated in the lamina did not significantly disrupt the adhesion process, and the same adhesion quality resulted.

Wood species and wood products affected hardness significantly. Manii, which had the lowest density, had the lowest hardness, while the other two species had much higher hardness, likely owing to their higher density. This outcome was in line with a report by Blaskova et al. [31], who indicated that a higher wood density had a higher hardness. According to Table 6, the hardness of mangium and rubber-wood were not significantly different, and they were both classified as medium-density wood.

With regard to wood products, solid wood had the lowest hardness, followed by untreated glulam and polystyrene glulam, which differed from each other. The untreated glulam was manufactured by placing the laminas with a higher MOE in the outer layers; with this technique, the strength of untreated glulam could be higher than the strength of its solid wood. If polystyrene glulam is examined, the polystyrene impregnation on the lamina could increase its hardness [8]. Consequently, the polystyrene glulam would have a higher hardness than the untreated glulam.

3.4. Delamination in Hot Water

The delamination test is used to assess the bonding quality of glulam. Specimens of impregnated polystyrene rubber-wood after delamination tests in hot water are presented in Figure 6, delamination values of glulam after treatment in hot water are shown in Figure 7, and the analysis of variance is summarized in Table 5. With regard to the analysis of variance, delamination was not affected by wood species or by wood products. All glulam specimens had a very good adhesion performance indicated by very low (less than 4%) delamination, and they fulfilled the JAS 234-2003 standard, which requires a maximum delamination in hot water of 10%.

Figure 6. Tested delamination specimens in hot water of polystyrene rubber-wood glulam.

From the discussion above, glulam can be seen to have had higher MOR, MOE, and hardness, but lower shear strength than its solid wood. Polystyrene glulam had lower MOR and MOE values than its untreated glulam, but it had a higher hardness value compared with untreated glulam. Both types of glulam were not significantly different in terms of

shear strength and delamination in hot water. To get better adhesion in polystyrene glulam, hot-press could be applied for the adhesive curing process.

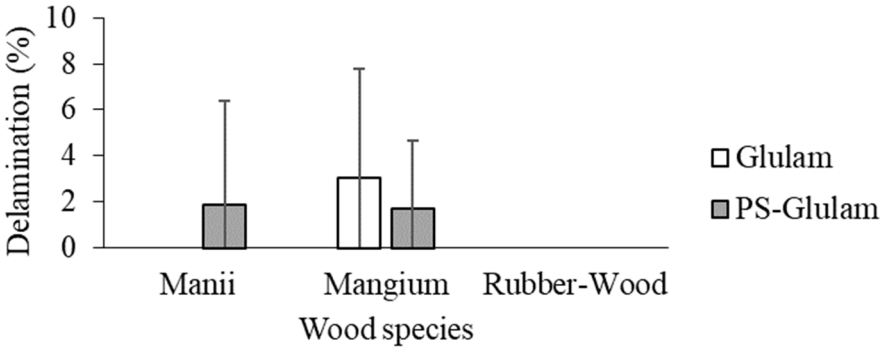


Figure 7. Delamination in hot water of glulam. PS = polystyrene.

Regarding the wood density for glulam manufacturing, at least a medium-density wood should be utilized, which would be more likely to produce a glulam that fulfills mechanical properties requirements. A lower wood density could be utilized for the inner part of the glulam, because this part would get a smaller compression force and tensile stress when the glulam is loaded [3].

With regard to the MOR, MOE, shear strength, and delamination in hot water requirements of JAS 234-2003, only rubber-wood glulams (untreated and polystyrene glulam) fulfilled the standard. Mangium glulams failed in MOE, and manii glulams failed in MOE and shear strength.

4. Conclusions

Based on our results, the color change of polystyrene glulam is very small (ΔE less than 2.0) compared with untreated glulam. In the physical properties, manii (*Maesopsis eminii*) wood belongs to low-density wood, while mangium (*Acacia mangium*) and rubber-wood (*Hevea brasiliensis*) belong to medium-density wood. With regard to the wood product, polystyrene glulam had the highest density, while untreated glulam was not significantly different from solid wood density. The MC of all wood products fulfilled the JAS 234-2003 standard, and they reflected the ambient moisture content in the area. In terms of mechanical properties, manii wood had the lowest MOR, MOE, shear strength, and hardness. Mangium wood had higher MOR and MOE values, equal hardness, and lower shear strength than rubber-wood. Concerning the wood product, solid wood had lower values for MOR, MOE, and hardness, but higher shear strength than the glulams (untreated and polystyrene glulam), while polystyrene glulam had lower MOR and MOE values, equal shear strength and wood failure, and higher hardness than untreated glulam. All the sample specimens of glulam had very good adhesion, which was indicated by the delamination in hot water being only 1.1%. With regard to the MOR, MOE, shear strength, and delamination in hot water requirements of JAS 234-2003, only rubber-wood glulams (untreated and polystyrene glulam) fulfilled the standard. Mangium glulams could not fulfill the MOE requirement, and manii glulams could not fulfill the requirements for MOE and shear strength. To attain adequate physical and mechanical properties of glulam, medium-density wood is recommended for glulam manufacturing.

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