The Physical and Mechanical Properties of Glulam Made from Pine and Jabon Woods

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Abstract

Wood from plantation forests can be used to make glued laminated lumber (glulam) products for structural applications. Wood from two species, namely pine (*Pinus merkusii*) and jabon (*Anthocephalus cadamba*), and polyurethane and tannin mahogany adhesives (glue spread 200 g m^{-2}) were used to manufacture glulams. The aim of this research was to determine the physical and mechanical properties of glulam made from pine and jabon woods. Wood densities of pine and jabon were 0.71 and 0.43 g cm^{-3}, respectively. The glulams consisted of three layers of the same wood species, and samples were (3×6×120) cm^3 in thickness, width, and length, respectively. The physical and mechanical properties of glulam were tested according to Japanese Agricultural Standard (JAS) 234-2007. The results showed that glulam made from pine met the standard for modulus of elasticity and modulus of rupture (MOR) values. Glulam made from jabon wood fulfilled the standard for MOR, shear strength, and hot- and cold-water delamination tests. In the formaldehyde emission test, jabon glulam fulfilled the F*** (low emission) standard and pine glulam met the F**** (very low emission) standard according to JAS 234-2007.

Keywords: glulam, fast-growing tree species, mahogany tannin adhesive, polyurethane adhesive

Abstrak

Penelitian ini menggunakan kayu yang berasal dari hutan tanaman sebagai bahan baku dalam pembuatan produk *glued laminated lumber* (glulam) dengan peruntukan aplikasi struktural. Dua jenis kayu yang digunakan yakni pinus (*Pinus merkusii*) dan jabon (*Anthocephalus cadamba*), direkat menggunakan 2 jenis perekat yakni *polyurethane* dan perekat tanin mahoni (dengan berat labur 200 g m^{-2}). Penelitian ini bertujuan untuk menentukan sifat fisis dan mekanis dari glulam yang terbuat dari kayu pinus dan jabon. Kerapatan kayu pinus dan jabon masing-masing adalah 0,71 dan 0,43 g cm^{-3}. Glulam terdiri atas tiga lapisan dari jenis kayu yang sama, dan masing-masing sampel memiliki ketebalan, lebar, dan panjang yakni (3×6×120) cm^3. Sifat fisis dan mekanis glulam diuji menurut *Japanese Agricultural Standard* (JAS) 234-2007. Hasil penelitian menunjukkan bahwa glulam yang terbuat dari kayu pinus memenuhi standar keteguhan lentur (MOE) dan keteguhan patah (MOR). Sementara, glulam yang terbuat dari kayu jabon memenuhi standar untuk MOR, kekuatan geser, dan tes delaminasi air panas dan dingin. Hasil uji emisi formaldehida menunjukkan bahwa glulam jabon memenuhi standar F*** (emisi rendah) dan pinus glulam memenuhi standar F**** (emisi sangat rendah) berdasarkan JAS 234-2007.

Kata kunci: glulam, jenis kayu cepat tumbuh, perekat *polyurethane,* perekat tanin mahoni

Introduction

In Indonesia, the raw material for the timber industry is logs that are mainly supplied from plantation forests (Hadi *et al.* 2010). According to the Indonesian Ministry of Environment and Forestry (2015), the total forest plantation area in 2014 reached 10.5 million hectares and predominantly contained pioneer trees or fast-growing species such as pine (*Pinus merkusii*) and jabon (*Anthocephalus cadamba*). These species have a cutting cycle of 5-10 years (Cahyono *et al.* 2012a, 2012b, 2017; Hadi *et al.* 2015). Trees of fast-growing species mostly contain sapwood, which has inferior physical and mechanical properties compared with heartwood (Fajriani *et al.* 2013). The quality of the wood can be improved by combining it with adhesives to manufacture composite products such as glued-laminated lumber (glulam).

Glulam is a structural timber product composed of several sheets of laminas that are bonded with adhesive in accordance with the desired lumber dimension. The properties of each lamina affects the strength of glulam. Moreover, the laminas can be arranged to increase the modulus of elasticity (MOE) and modulus of rupture (MOR) values of the glulam product (Komariah *et al.* 2015). Laminas with a high MOE value are placed on the outside (face and back layers) of the glulam, and laminas with a low MOE value are placed in the middle (core layer) and under the outside layer of the glulam.

Aside from the laminas, the other component that determines the quality of glulam is the adhesive used. Adhesives are commonly made from synthetic compounds, and polyurethane (PU) is one such synthetic adhesive that is used in the wood industry. PU adhesives are increasingly being used in structural joinery applications because they offer advantages in terms of damping impact, flexibility, high cohesive strength, low-temperature performance, and amenable curing speeds (Banea *et al.* 2015).

Another type of adhesive, called bio-adhesive, is made from natural materials. The advantages of bio-adhesives are that they are made from renewable resources and are environmentally friendly (Santoso *et al.* 2014, 2016). Tannins are polyphenolic compounds found in plants and trees, particularly in bark (Yi *et al.* 2016). Previous research investigated the manufacture of glulam using a bio-adhesive based on tannins extracted from the bark of mahogany (*Swietenia mahagony* (L.) Jacq) (Lestari *et al.* 2015, Cahyono *et al.* 2017). This bio-adhesive yielded similar results compared with the synthetic adhesive methylene diphenyl diisocyanate (MDI).

The aim of the current study was to produce glulam that met structural Japanese Agricultural Standard (JAS) standard for physical and mechanical properties. Glulam was manufactured from the wood of two fast-growing tree species, and samples made with mahogany tannin bio-adhesive were compared with samples containing PU-based synthetic adhesive.

Materials and Methods

Glulam manufacture

Pine (around 7-9 years old) and jabon (around 5-7 years old) trees were harvested from Bogor, West Java, Indonesia. The wood of each species was cut into sheets of lamina measuring (1×6 ×120) cm^3 in thickness, width, and length, respectively. The lamina were air dried and then dried in a kiln until reaching air-dried condition (approximately 12 percent moisture content). The MOE of each lamina was predicted through nondestructive testing with a panther device (Panther version MPK-5), following Lestari *et al.* (2015). Laminas with higher MOE values were used for the face and back layers of the glulam, and those with lower values were placed in the core.

For each species, three layers of laminas were bonded with either mahogany tannin bio-adhesive or PU adhesive (PU 095, PT. Barakat Arghad Sejati, Jakarta, Indonesia) with the double-spread method at a glue spread of 200 g m^{-2}. The bio-adhesive was made by mixing mahogany tannin extract, resorcinol, and formaldehyde (10 ml of formaldehyde per 100 ml of tannin extract, 5% of resorcinol as addition (w/v)). Glulam was pressed using a cold press machine at a pressure of 8 kg cm^{-2} for 4 hours. The resultant three-layer homogeneous glulam was (3×6×120) cm^3 in thickness, width, and length, respectively, as shown in Figure 1. Solid wood samples for both samples with the same dimensions as the glulam were prepared for comparison purposes. Three replicates were made for glulam of each factor (type of wood and adhesive) and solid wood of each type of wood.

Glulam testing methods

The physical and mechanical properties of the glulams were tested according to JAS 234-2007 for glue laminated timber (JSA 2007). Glulam cutting models are shown in Figure 2.

Figure 1 The sample of three-layer homogeneous glulam from jabon wood using tannin adhesive.

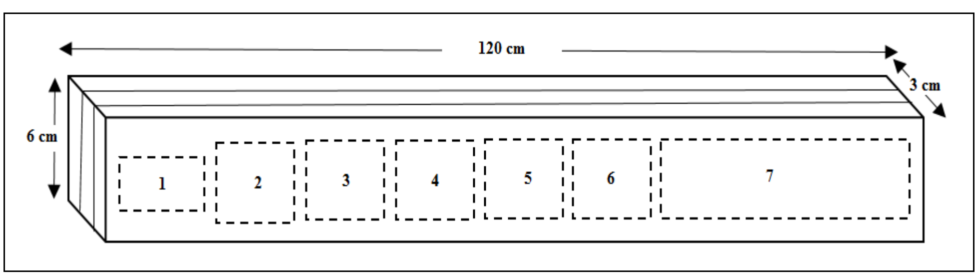

Figure 2 Cutting model of glulam for each test specimen 1). Test specimen for formaldehyde emission (2.5×5×3) cm^3, 2) Test specimen for shear strength (5×5×3) cm^3, 3). Test specimen for density (5×5×3) cm^3, 4). Test specimen for moisture content (5×5×3) cm^3, 5). Test specimen for delamination (in hot water) (5×5×3) cm^3, 6). Test specimen for delamination (in cold water) (5×5×3) cm^3, 7). Test specimen for MOR and MOE (5×45×3) cm^3.

Physical properties test

Physical properties were tested based on the moisture content and density, which were calculated with the following formulas:

Moisture content (%)=

$$\frac{\text{Initial weight - Oven-dried weight}}{\text{Oven-dried weight}} \times 100$$

$$\text{Density (g cm}^{-3}\text{)} = \frac{\text{Air-dried weight (g)}}{\text{Air-dried volume (cm}^3\text{)}}$$

Mechanical properties test

Mechanical properties were tested by using an Universal Testing Machine Instron (type 3369) for the MOR, MOE, and shear strength. MOE and MOR were calculated with the following formulas:

$$\text{MOE (kg cm}^{-2}\text{)} = \frac{\Delta PL^3}{4\ \Delta Y\ bh^3}$$

$$\text{MOR (kg cm}^{-2}\text{)} = \frac{3PL}{2\ b\ h^2}$$

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 the 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 shear strength was calculated using the following formula:

Shear strength (kg cm^{-2})=

$$\frac{\text{Rupture load (kg)}}{\text{Area of bonding layer (cm}^2\text{)}}$$

Delamination test

Both cold-water delamination and hot-water delamination tests were conducted. The cold-water delamination test was carried out by soaking test specimens in water at room temperature for 6 hours and then placing them in the oven at 40±3 °C for 18 hours. Hot-water delamination was tested by boiling the specimens in water (100 °C) for 4 hours and then soaking them in room temperature water for 1 hour. The specimen were then placed in the oven at 70±3 °C for 18 hours. Delamination ratio was calculated using formula:

Delamination ratio(%) =

$$\frac{\text{Sumof delaminated lengths of two cross sections}}{\text{Sum of gluing lengths of two cross sections}} \times 100$$

Formaldehyde emission

For formaldehyde emission testing, samples sized (2.5×3×5) cm^3 in width, thickness, and length, respectively, were hung in a bottle containing 25 ml of distilled water without contact with the water. The bottle containing the sample was placed in an oven at 40±2 °C for 24 hours. Afterward, 10 ml of water was taken from the bottle and combined with 10 ml of acetyl ammonium acetate reagent. The mixture was measured with a spectrophotometer at λ = 412 nm to determine the formaldehyde concen-tration. The schematic diagram of the test is shown in Figure 3.

Data analysis

Previous studies showed that jabon has a density of 0.41 g cm^{-3} (Hermawan *et al.* 2012) and pine has a density of 0.69 g cm^{-3} (Hadi *et al.* 2016). Since wood densities differed, data analysis was undertaken using a completely randomized block design. The block factor was wood species (i.e., jabon or pine), and the treatment factor was the type of adhesive (i.e., bio-adhesive, PU, or no adhesive in the case of solid wood). If from the analysis of variance the treatment factor was significantly different ($P<0.05$), Duncan's multi-range test was used for further analysis.

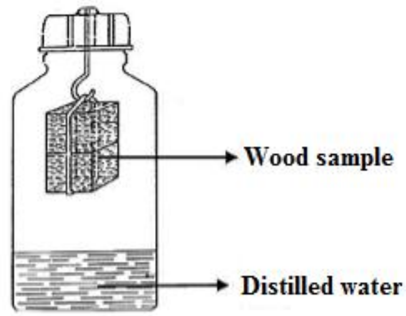

Figure 3 The scheme of the formaldehyde emission test.

Results and Discussions

Physical properties of glulam

The physical (density and moisture content) and mechanical (MOE, MOR, and shear strength) properties of the glulam and solid wood samples are shown in Table 1, and the results of the delamination and formaldehyde emission tests are shown in Tables 4 and 5, respectively.

Density

Glulam and solid jabon wood had densities of 0.36 to 0.45 g cm^{-3}, which were lower than those of pine (0.67 to 0.71 g cm^{-3}) as shown in Table 1. These results were similar to those reported by Hadi *et al.* (2013). According to the analysis of variance presented in Table 2, wood species had a highly significant effect on the density of glulam. The density of glulams was affected by density of its component wood, with higher-density wood producing higher density glulam. In this research, the lumber came from many logs, resulting in highly variable density. In addition, the lumber contained a high proportion of sapwood even though the samples were from the same wood species. From Figure 1, it can be seen that the laminas of glulam had different colors, with a darker color corresponding to a higher density. The type of adhesive did not affect the density of glulam because the glue lines were very thin and did not increase the mass of the glulam. This result is in accord with Komariah *et al.* (2015), who found no effect of pressure on the density of glulam.

Mechanical properties of glulam

Modulus of elasticity

Pine glulam and solid pine wood had higher MOE values than jabon glulam and solid jabon wood (shown in Table 1), but neither glulam met JAS 234-2007 (minimum 75 000 kg cm^{-2}). As shown by the analysis of variance (Table 2), the MOE of glulam was not affected by the type of wood, but it was affected by the type of adhesive. According to Duncan's multi-range test (Table 3), the MOE of solid wood was significantly different from those of the glulams constructed with bio-adhesive and PU adhesive, but the MOE values of the glulams were not different from each other. This phenomenon may be caused by the adhesion quality of glulam being unsatisfactory and needing to be improved. Increasing glue spread could provide better adhesion quality refer to Komariah *et al.* (2015), which uses glue spread 280 g m^{-2} obtain good mechanical test result.

Modulus of rupture

Pine glulam and pine solid wood had a high MOR and fulfilled JAS 234-2007 (more than 75 000 kg cm^{-2}), but jabon glulam and solid jabon wood did not fulfill the standard. Notably, jabon wood has a low density (0.45 g cm^{-3}) compared with pine wood (0.71 g cm^{-3}), and Hadi *et al.* (2013) reported that lower-density wood has lower mechanical property values.

Table 1 Physical and mechanical properties of glulam and solid wood

Wood species	Physical properties			Mechanical properties		
	Adhesive	Density, g cm^{-3}	Moisture content, %	MOE × 1000, kg cm^{-2}	MOR, kg cm^{-2}	Shear strength, kg cm^{-2}
Pine	Tannin	0.67 ± 0.02	12.14 ± 0.36	62 ± 03	350 ± 057	48 ± 14
	PU	0.68 ± 0.07	11.92 ± 1.02	71 ± 10	416 ± 149	99 ± 31
	Solid[a)]	0.71 ± 0.01	11.12 ± 0.50	106 ± 03	742 ± 011	140 ± 06
Jabon	Tannin	0.36 ± 0.02	12.06 ± 0.38	49 ± 07	307 ± 002	73 ± 08
	PU	0.45 ± 0.04	12.01 ± 0.45	61 ± 10	363 ± 065	60 ± 17
	Solid[a]	0.43 ± 0.05	12.44 ± 0.50	81 ± 02	548 ± 067	57 ± 03
JAS requirement			Max 15	Min 75	Min 300	Min 54

Note: [a)] : source from Lestari *et al.* (2015).

The MOR value was also affected by the type of adhesive, as shown in the analysis of variance (Table 2). Based on the Duncan's multi-range test presented in Table 3, the MOE of solid wood had a higher value and was significantly different from both glulams. The glulams were not different from each other, however. This result was similar to the result of the MOE test and indicated that the mechanical properties of glulam made with bio-adhesive were not different from those of PU glulam.

Shear strength

Shear strength is the main benchmark for analyzing the quality of gluing. Table 1 shows that pine glulam had a higher shear strength value than jabon. Pine glulam using the bio-adhesive did not fulfill the JAS requirement. Pine wood has a high density, which may have impeded penetration of the tannin adhesive. Jabon glulam using tannin adhesive and PU fulfilled the JAS requirement, with a shear strength that exceeded that of the solid jabon wood.

The analysis of variance results (Table 2) indicated that the type of wood and the type of adhesive in glulam did not affect the shear strength, indicating that the adhesion quality was good and the adhesion quality of mahogany tannin extract was not different from that of the PU adhesives.

Delamination test

The results of the cold-water delamination test (Table 4) indicated that only pine glulam with tannin adhesive underwent delamination. Pine glulam using the PU adhesive and jabon glulams using either type of adhesive had no delamination. According to JAS 234-2007 (JSA 2007), pine glulam using PU and jabon glulams fulfilled the Japanese standard of less than 5% delamination.

In the hot-water delamination test, pine glulam with the tannin adhesive or PU adhesive had a higher delamination value compared with jabon glulam. Jabon glulam using tannin adhesive also had delamination. Nevertheless, jabon glulam still fulfilled the JAS 234-2007 (JSA 2007) requirement of less than 10% delamination. As in the cold-water test, jabon glulam showed no delamination.

Table 2 ANOVA of the physical and mechanical properties of glulam

Parameter	Wood species	Adhesive
Density	**	NS
Moisture content	NS	NS
MOR	NS	**
MOE	NS	**
Shear strength	NS	NS
Delamination in cold water	**	**
Delamination in boiling water	**	**

Note: **Significant ($P < 0.05$); NS = not significant.

Table 3 Duncan's multi-range test of physical and mechanical properties[a]

Adhesive	MOE	MOR	Delamination	
			Hot water	Cold water
Tannin	55742 a	328 a	0.00 a	0.00a
PU	66199 a	389a	12.03 a	0.00a
Solid	93828 b	645 b	24.50 b	12.84b

Note: [a]Values followed by the same letters within a column are not significantly different.

Table 4 Glulam delamination test.

Wood species	Adhesive	Delamination ratio, %	
		Cold water	Hot water
Pine	Tannin	25.7 ±5.2	44.9 ± 01.0
	PU	0.0 ± 0.0	41.79 ± 12.9
Jabon	Tannin	0.0 ± 0.0	3.79 ± 01.1
	PU	0.0 ± 0.0	0.0 ± 00.0
JAS requirement		Max 5	Max 10

For exterior use, jabon glulam fulfilled JAS requirements for both cold-water (maximum 5%) and hot-water conditions (maximum 10%). These results were similar to those of Carvalho *et al.* (2014), which indicated that tannin adhesive from Barbatimão used for plywood had a good performance in both humid and dry environments.

Formaldehyde emission

Formaldehyde emissions occur because unreacted formaldehyde in the resin is released into the environment. Formaldehyde emissions at certain levels cause various adverse health problems in people who are exposed, including a burning sensation in the eyes, nose, and lungs; dizziness; and vomiting (Roffael 1993, ATSDR 2008). Table 5 shows that formaldehyde emissions of jabon glulam could be classified as F*** which have a low emission (0.4–0.7 mg l^{-1}), and pine glulam could be classified as F**** which have a very low emission (less than 0.4 mg l^{-1}) according to JAS 234-2007 (JSA 2007).

Table 5 Formaldehyde emissions from glulam

Wood species	Formaldehyde emissions, mg l^{-1}	Grade[a)]
Pine	0.01	F**** (very low)
Jabon	0.62	F*** (low)

Note: [a)] Categorized by JAS 234-2007.

Conclusion

Based on the physical and mechanical test results, the density and shear strength of the glulams did not different from those of solid wood of either species tested. Pine glulam using PU adhesive had the highest mechanical values (MOE, MOR, and shear strength) and fulfilled the JAS 234-2007 requirements. Jabon glulam met JAS 234-2007 requirements for MOR and shear strength values. The mechanical properties of glulam were affected by the density of each glulam. In the delamination test, jabon glulam fulfilled the JAS requirement, and for the formaldehyde emission test, all glulams fulfilled the JAS requirement (F**** /very low emission for pine glulam, and F***/low emission for jabon glulam).

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