

## Glulam Properties of Fast-growing Species Using Mahogany Tannin Adhesive

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Manufacturing glued laminated timber (glulam) can help overcome the limited availability of large-sized timber, and the use of bio-adhesives may resolve environmental problems associated with synthetic adhesives containing high formaldehyde contents. Tannin adhesive is a bio-adhesive that can be used as alternative glue in the manufacture of glulam. The purpose of this study was to determine the physical and mechanical properties of glulam made with mahogany (*Swietenia* sp.) tannin adhesive and wood from three fast-growing species, namely pine (*Pinus merkusii*), jabon (*Anthocephalus cadamba*), and sengon (*Falcataria moluccana*). Glulam (3 cm × 6 cm × 120 cm in thickness, width, and length, respectively) was manufactured with three layers of lamina. The physical and mechanical properties of the glulams were tested based on relevant standards. The results showed that pine glulam fulfilled the standard for the modulus of rupture and modulus of elasticity, while sengon glulam met the standard for shear strength. In the delamination test, sengon glulam was resistant to immersion in cold water and hot water. All glulams had low formaldehyde emission levels and therefore fulfilled the standard requirements. The results showed that the tannin adhesive from mahogany bark was equal in quality to methylene diphenyl di-isocyanate for glulam manufacturing.

*Keywords:* Glulam; Fast-growing species; Tannin adhesive; Formaldehyde emission

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### INTRODUCTION

Shortages in the availability of high-quality and large-sized timber can be overcome by using glued laminated timber (glulam) instead. Recently, the use of fast-growing wood species that produce small-diameter logs (less than 30 cm) has been intensively explored in the context of glulam manufacture. Plantation forests have been developed and planted primarily with fast-growing tree species such as pine (*Pinus merkusii*), jabon (*Anthocephalus cadamba*), and sengon (*Falcataria moluccana*) that have a cutting cycle of 5 to 10 years (Hermawan *et al.* 2012). These forests produce a higher proportion of juvenile wood than mature wood (Fajriani *et al.* 2013). Juvenile wood has lower density, lower stiffness (modulus of elasticity [MOE]), and lower strength (modulus of rupture [MOR]) (Clark *et al.* 2006). The wood is rarely used as a raw material for structural lumber, but manufacturing biocomposite products such as glulam is one way to improve the wood quality.

The characteristics of glulam are influenced by the properties of each lamina, and the laminas can be arranged in such a way that improves the strength properties of glulam (Komariah *et al.* 2015). In addition to the wood, glulam manufacture requires the use of

adhesives. Synthetic adhesives are made from nonrenewable raw materials, contain high formaldehyde contents, and their availability will steadily decrease with time (Santoso *et al.* 2014). Natural adhesives have therefore been developed to reduce and possibly replace the use of synthetic adhesives in biocomposite product manufacturing.

Mahogany (*Swietenia* sp.) is a premium wood in Indonesia. Given its strength and interesting appearance, it is widely used for building and furniture manufacture. Indonesia produced approximately 130,864 m<sup>3</sup> of mahogany in 2014 (Perum Perhutani 2014). In Jepara in Central Java, the center of the furniture industry, mahogany is one of the main raw materials for manufacturing furniture such as cupboards, chairs, tables, and bedroom sets (Fadillah *et al.* 2014). Its use generates a lot of bark waste, a part of the plant that typically has a fairly high tannin content (Hagerman 2002). Tannin contains polyphenolic compounds that can be used as raw materials for manufacturing natural adhesives, also known as bio-adhesives. Utilizing tannins for bio-adhesives has been previously studied with tannins derived from mangium (*Acacia mangium*), merbau (*Intsia bijuga*), mangrove (*Rhizophora* sp.), and pine (Pizzi 1982; Santoso *et al.* 2014).

The objective of this study was to determine the physical and mechanical properties of glulam made with mahogany tannin adhesive and three types of fast-growing wood species.

## EXPERIMENTAL

### Extraction and Modification of Mahogany Tannin

Tannins were extracted from dried, powdered mahogany stem bark with a hot-water extraction apparatus, and the tannin extracts were modified by heating with distilled water and 20 mL of 5% NaOH solution in the hot-water apparatus. Qualitative testing of tannins was carried out using a 0.1 M ferric chloride solution and the Lieberman test (Akoto and Osei-Brefoh 2014)

The reactivity of polyphenols in tannin towards formaldehyde (Stiasny number) was ascertained as follows: 20 g of unmodified dehydrated extract was added to a beaker containing 40 mL of water. The solution was then adjusted to pH 7 by adding sodium hydroxide pellets. One hundred milliliters of formalin and 15 mL of concentrated HCl were added, and the mixture was heated at 90 °C for 85 min. The resulting solution was vacuum-filtered, and the solid residue was washed with hot water, dehydrated, oven-dried at 105 °C, and weighed. The Stiasny number was determined according to the following equation:

$$\text{Stiasny precipitation number} = \frac{\text{Dry weight of solid residue}}{\text{Dry weight of extracts}} \times 100 \quad (1)$$

### Preparation of Mahogany Tannin Adhesive

Mahogany tannin adhesives were made by mixing mahogany tannin extract and formaldehyde (10 mL formaldehyde per 100 mL of extract tannins). The mixture was then stirred for approximately 15 min.

### Analysis of Tannin Extract and Adhesive

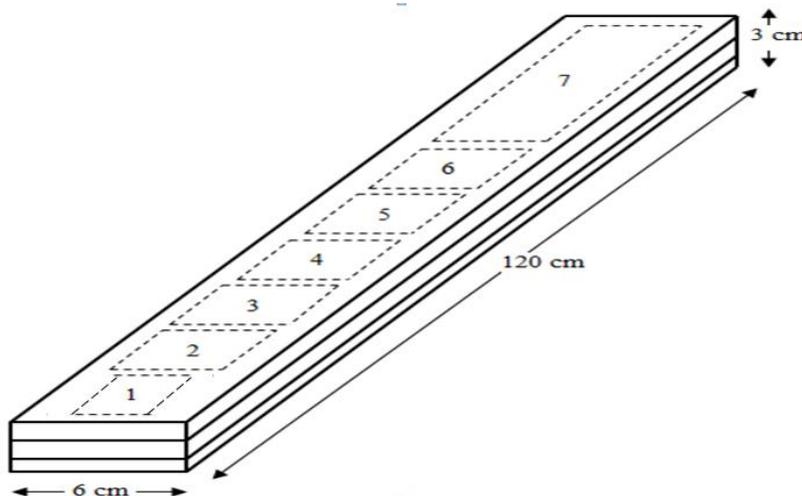
The tannin extract and the adhesive were analyzed by Fourier transform infrared (FTIR-1600, Shimadzu, Japan) spectroscopy to determine the functional groups, and tannin compounds were analyzed by pyrolysis gas chromatography-mass spectrometry (Py-GCMS-QPXP-2010, Shimadzu, Japan).

## Preparation of Glulam

Glulam was made from three wood species, namely pine (7 to 9 years old), jabon, and sengon (both 5 to 7 years old), harvested from Bogor, West Java, Indonesia. Lamina sheets were manufactured from the lumber to be 1 cm × 6 cm × 120 cm in thickness, width, and length, respectively. The laminas were dried naturally and then kiln-dried to a moisture content of approximately 12%. Lamina sorting was performed by MOE prediction using a non-destructive device (Panther version MPK-5) for quality sorting. Laminas used for the face and back layers of glulam had higher MOE values, while the core laminas had lower MOE values. Each lamina was bonded using either the mahogany tannin adhesive, with a solids content of 10% and viscosity 29.2 cp, or isocyanate, a water-soluble polymer consisting of a base resin and hardener. Glue was double spread at 200 g/m<sup>2</sup>, then the glulam was pressed using a cold press machine at a pressure of 8 daN/cm<sup>2</sup> for 4 h, and then clamped for 20 h. The resultant three-layer homogeneous glulam measured 3 cm × 6 cm × 120 cm in thickness, width, and length, respectively. Solid wood samples that were the same size as the glulam were prepared for comparison, and the number of replication was three.

## Glulam Testing Methods

The physical and mechanical properties of glulam were tested according to the Japan Agricultural Standard (JAS) for glue laminated timber (JAS 234-2003 (2003)). Glulam cutting models are shown in Fig. 1.



1. Sample testing for formaldehyde emission (2.5 cm × 5 cm × 3 cm)
2. Sample testing for shear strength (5 cm × 5 cm × 3 cm)
3. Sample testing for density (5 cm × 5 cm × 3 cm)
4. Sample testing for moisture content (5 cm × 5 cm × 3 cm)
5. Sample testing for delamination (in hot water) (5 cm × 5 cm × 3 cm)
6. Sample testing for delamination (in cold water) (5 cm × 5 cm × 3 cm)
7. Sample testing for MOR and MOE (5 cm × 45 cm × 3 cm)

**Fig. 1.** Cutting model of glulam for each test specimen

### *Physical and mechanical properties*

Physical properties were tested based on the moisture content and density, and mechanical properties were tested with a Universal Testing Machine (Instron type 3369,

USA) to determine the MOR, MOE, and shear strength. For MOR and MOE tests, one point loading was applied with the span of 42 cm, and load speed 3 mm/minute.



Fig. 2. MOR and MOE test using Universal Testing Machine

### Delamination Ratio

The delamination test consists of two parts, namely cold water delamination and hot water delamination tests. The cold water delamination test was carried out by soaking the test specimen in water at room temperature for 6 h, then putting the specimen into the oven at a temperature of  $40 \pm 3$  °C for 18 h. Hot water delamination was done by boiling the test specimen in water (100 °C) for 4 h, then soaking it in water at room temperature for 1 h. Furthermore, the specimen was put into an oven at a temperature of  $70 \pm 3$  °C for 18 h. The delamination ratio was calculated using Eq. 7.

$$\text{Delamination ratio(\%)} = \frac{\text{Sum of delaminated lengths of two cross sections}}{\text{Sum of gluing lengths of two cross sections}} \times 100\% \quad (7)$$

### Formaldehyde Emissions

To test formaldehyde emissions, samples sized  $2.5 \text{ cm} \times 3 \text{ cm} \times 5 \text{ cm}$  were hung in a bottle containing 25 mL of distilled water. The samples were not in contact with the water. The bottle containing the sample was placed in an oven at  $40 \pm 2$  °C for 24 h. The formaldehyde concentration in the sample solution was measured with a spectrophotometer at  $\lambda = 412 \text{ nm}$ , and 10 mL of sample solution was added to 10 mL of acetyl ammonium acetate reagent.

### Data Analysis

The data was analyzed by using SPSS Statistics 20 (IBM, USA). Solid wood and glulam data were compared using Student's *t*-test. For the glulam data analysis, regarding the different density of the three wood species, *i.e.* sengon  $0.32 \text{ g/cm}^3$ , jabon  $0.43 \text{ g/cm}^3$ , and pine  $0.71 \text{ g/cm}^3$ , data analysis was undertaken using a completely randomized block design. The block factor was wood species (*i.e.*, sengon, jabon, and pine), and the treatment factor was the type of adhesive (*i.e.*, tannin adhesive and methylene diphenyl diisocyanate [MDI]). If the block factor was significantly different, Duncan's multi-range test was used for further analysis.

## RESULTS AND DISCUSSION

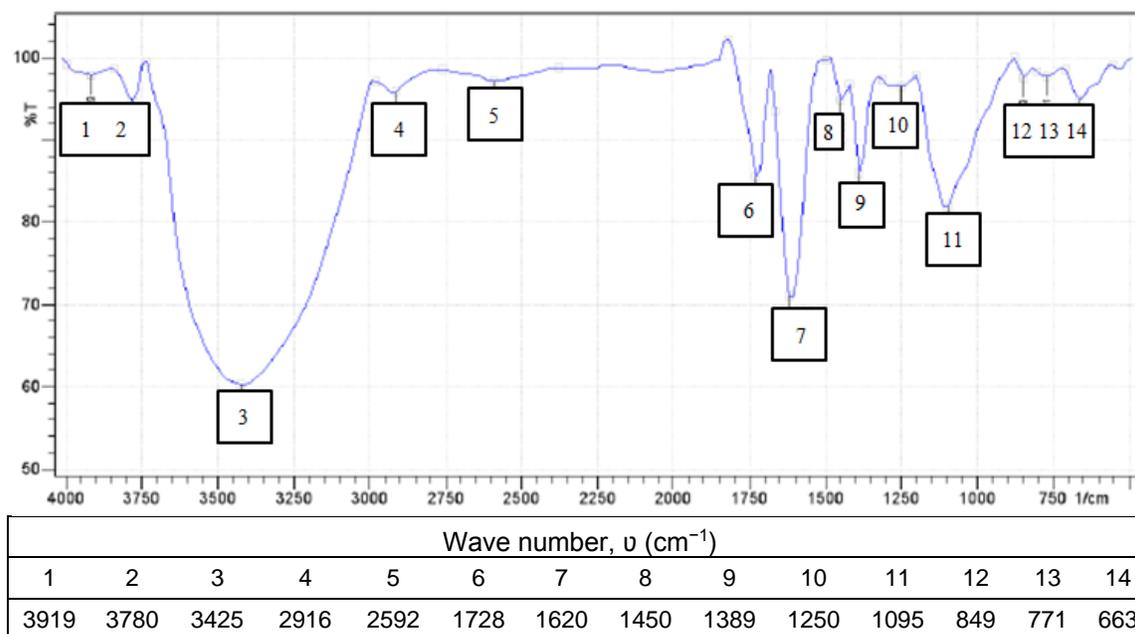
### Analysis of Mahogany Tannin Extract

The Stiasny number indicates that the extract contains tannin, with a value of 100% indicating the highest content of reactive polyphenol available for polymerization (FAO 2000). The percentage of tannin extract in 1 kg mahogany bark was 24% with a Stiasny number of 79.7% (w/w), indicating that the extract has good suitability for use as a resin.

#### FTIR spectroscopy

Figure 2 shows a wave number of  $3425\text{ cm}^{-1}$  on the spectrograph, indicating that the mahogany tannin extract contains hydroxyl groups (Table 1) (Supratman 2010). In addition, a wave number at  $1728\text{ cm}^{-1}$  indicates a carbonyl group compound, with the wave number ranging from  $1650$  to  $1800\text{ cm}^{-1}$  (Table 1).

Wave number  $1620\text{ cm}^{-1}$  is an aromatic ring vibrational wave that ranges from  $1500$  to  $1675\text{ cm}^{-1}$ . Furthermore, a wave number of  $1450\text{ cm}^{-1}$  indicates the aromatic aldehyde group, with numbers ranging from  $1300$  to  $1475\text{ cm}^{-1}$ . A wave number of  $1250\text{ cm}^{-1}$  indicates an ether group, according to Table 1.



**Fig. 3.** Spectrograph of mahogany tannin extract

These results indicated that the functional groups identified by FTIR spectroscopy were hydroxyl, carbonyl, vibration aromatic ring, aromatic aldehydes, and ether, and these compounds were similar to the groups in tannic acid as a standard (Hindriani 2005). Thus, the mahogany bark extract contained tannin compounds.

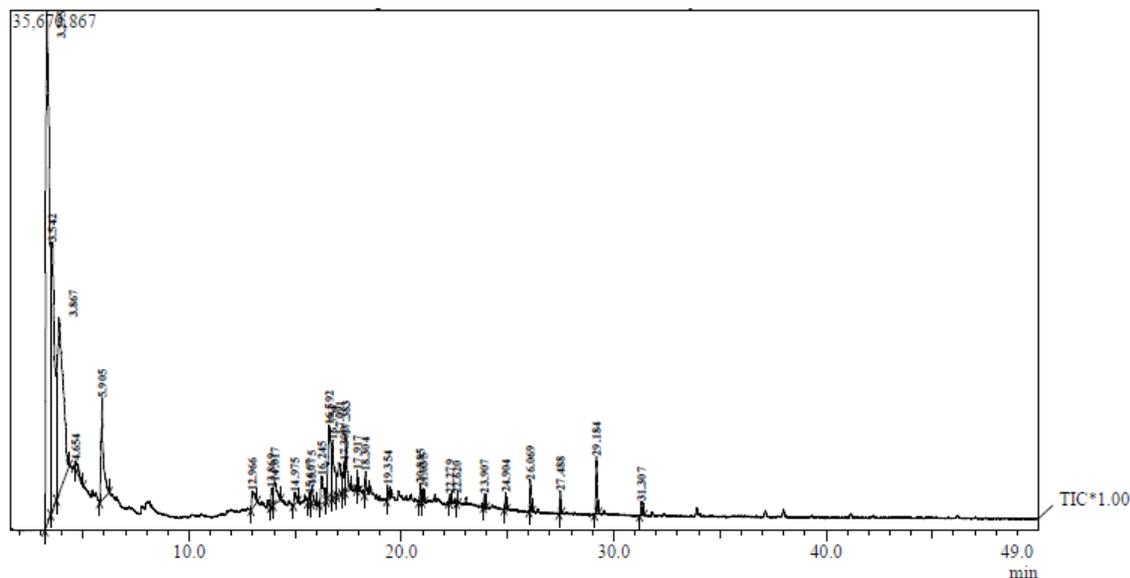
**Table 1.** Spectrophotometric Absorption Band of Tannin and Tannin Extract Mahogany

No.	Tannin standard*	Mahogany tannin extract	Range standard of absorbance**	Description**
1	3335	3425	2500-3500	Hydroxyl group
2	1710	1728	1650-1800	Carbonyl group
3	1610	1620	1500-1675	Aromatic ring vibration
4	1440	1450	1300-1475	Aromatic aldehyde
5	1320	1250	1000-1300	Ether group

\* Hindriani (2005)

\*\* Supratman (2010)

The pyrolysis GCMS chromatograph (Fig. 3) indicates that mahogany tannin extract contains guaiacol phenol, based on a retention time of 13.869 min, at a concentration of 0.55%. The retention time of 14.017 min corresponds with *o*-cresol phenol compounds at a concentration of 1.44%; 16.754 min is 1,4-benzenediol 2-methyl at 2.49% concentration; 17.091 min is 2-methoxy-4-methylphenol, at a concentration of 1.94%; and 19.354 min is phenol 4-allyl-2,6-dimethoxyphenol at a concentration approaching 0.39%.

**Fig. 4.** Chromatograph of mahogany tannin extract

#### GCMS Pyrolysis

Based on the results of FTIR analysis and the results from the pyrolysis GCMS, phenolic compounds accounted for 6.81% of the extract. The mahogany tannins contained enough polyphenol compounds that a reaction with formaldehyde would yield a product resembling phenol formaldehyde (Pizzi 1994). Therefore, it has the potential to be used as an adhesive, similar to merbau tannins, as reported by Santoso *et al.* (2014).

## Analysis of Mahogany Tannin Adhesive

### FTIR spectroscopy

The absorption band by FTIR spectroscopy (Fig. 4) indicated a shift in the wave number for the mahogany tannin adhesive compared with the mahogany tannin extract. The intensity of the hydroxyl group increased, with the peaks shifting to greater numbers and reaching  $3472\text{ cm}^{-1}$ . The intensity of the vibration of aromatic ring and aromatic aldehydes decreased, undergoing a shift towards smaller numbers and dropping to  $1589\text{ cm}^{-1}$  for the aromatic ring and  $1358\text{ cm}^{-1}$  for aromatic aldehydes. In addition, the tannin adhesive showed the presence of methylene, which was marked by a wave at  $2850\text{ cm}^{-1}$ , and aldehyde at  $2700\text{ cm}^{-1}$ , indicating that a new group formed after the addition of formaldehyde. According to Achmadi (1990), a copolymerization reaction occurs between tannin and formaldehyde in alkaline conditions. However, the ether bridges linking the compounds are unstable, and free formaldehyde is released to form a more stable methylene bridge. Methylene bridges ( $-\text{CH}_2-$ ) were identified at wave number  $2850\text{ cm}^{-1}$ .

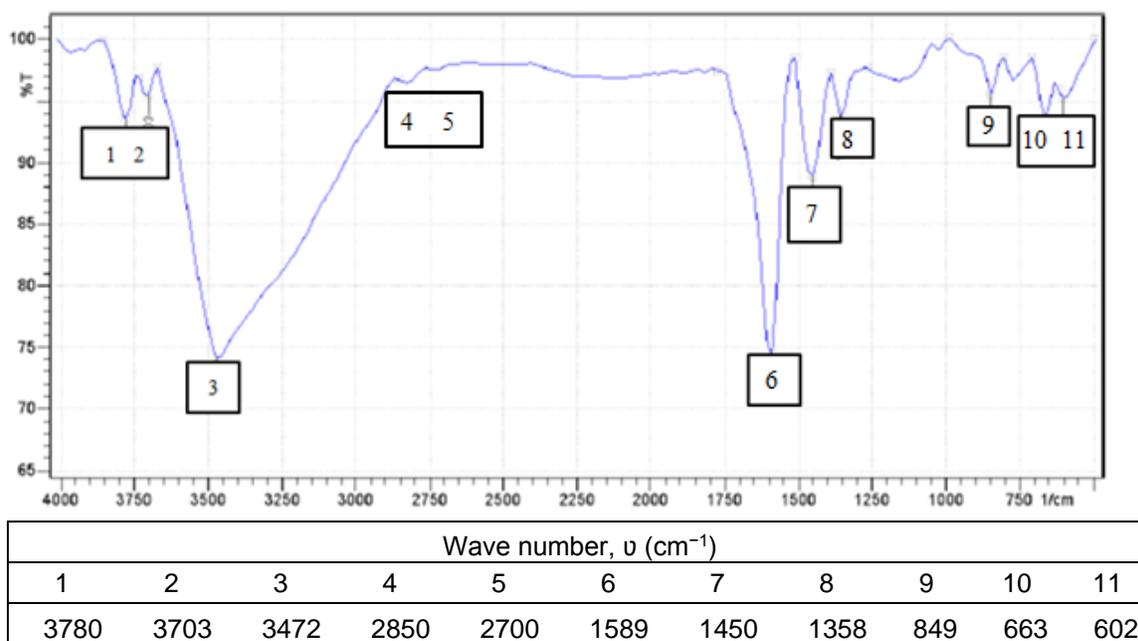
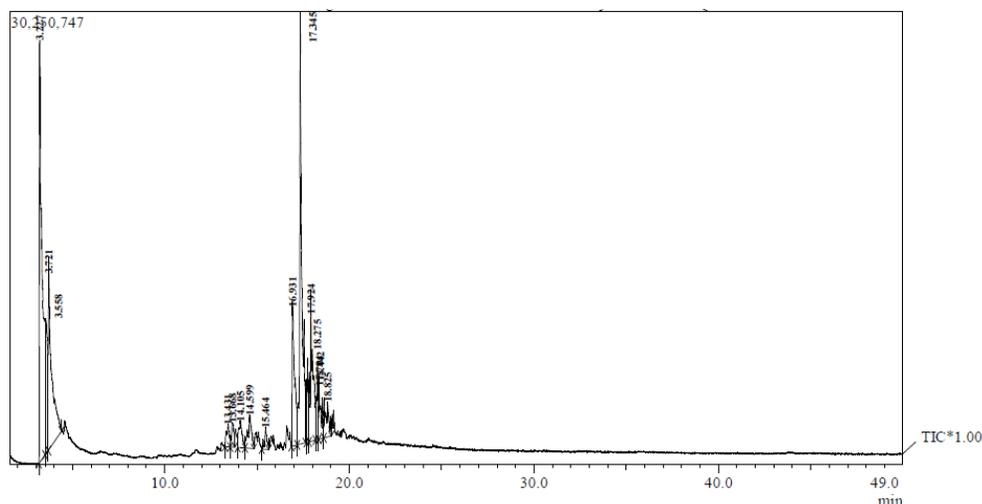


Fig. 5. Spectrograph of mahogany tannin adhesive

### GCMS pyrolysis

After the addition of formaldehyde, each of the phenolic compounds underwent a change in retention time and concentration, as shown in the chromatograph in Fig. 5. The retention time of phenol *o*-cresol became 13.668 min, with a 1.38% concentration. Meanwhile, new compounds formed, such as 2,3-dimethylphenol phenol, with retention times of 14.105 and 14.599 min at concentrations of 2.00% and 2.59%, respectively. Phenol 1-hydroxy-3-methyl-6-ethylbenzen had a retention time of 15.464 min, with a concentration of 1.11%, and 1,2-benzenediol 4-tert-butylpyrocatechol had a retention time of 17.924 min with 8.42% concentration. In addition, resorcinol-containing compounds had a high concentration (7.74%) and a retention time of 16.931 min.



**Fig. 6.** Chromatograph of mahogany tannin adhesive

The FTIR and pyrolysis GCMS analyses of mahogany tannin adhesive indicated that the addition of formaldehyde to mahogany tannin extract created new groups, namely aldehyde and methylene bridges. In addition, the levels of polyphenols increased to 23.24%, and a resorcinol-containing compound, similar to that found in merbau tannin adhesive (Santoso *et al.* 2014), was detected.

## Physical Properties of Glulam

### Density

The physical properties of glulam and solid wood are shown in Table 2. Glulam and solid sengon wood had the lowest densities (0.27 to 0.32 g/cm<sup>3</sup>), followed by jabon (0.37 to 0.47 g/cm<sup>3</sup>) and pine (0.60 to 0.71 g/cm<sup>3</sup>). However, no significant difference was found between the densities of solid wood and glulam based on Student's *t*-test (Table 3). These results were similar with Komariah *et al.* (2015), who showed that there was no effect of pressure on compressed glulam.

According to the analysis of variance presented in Table 4, wood species had a highly significant effect on the density of glulam; the glulam density varied widely, ranging from 0.28 to 0.63 g/cm<sup>3</sup> (Table 5). The density of glulams was affected by the density of the component woods. Sengon has a density 0.32 g/cm<sup>3</sup>; jabon, 0.43 g/cm<sup>3</sup>; and pine, 0.71 g/cm<sup>3</sup>. The type of adhesive did not affect the density of glulam because glue lines were very thin and did not increase the mass of the glulam.

### Moisture content

Table 2 shows that the moisture content of the glulam ranged from 10.40% to 12.97%. The moisture content fulfilled the JAS 234-2003 (2003) standard, which sets the allowable moisture content in glulam at less than 15%. As shown in Table 3, the moisture content of solid wood (11.13%) differed from that of glulam (12.49%) because glulam had a glue line with water-soluble adhesive and was cold-pressed during the manufacturing process, both of which increased its moisture content. According to the analysis of variance shown in Table 4, the moisture content of glulam was not affected by the wood species and type of adhesive. The moisture content of all glulams was 12.49 ± 0.45% and tended to reach equilibrium moisture content.

**Table 2.** Physical and Mechanical Properties of Glulam and Solid Wood

Wood species	Adhesive	Physical		Mechanical		
		Density (g/cm <sup>3</sup> )	Moisture content (%)	MOE (daN/cm <sup>2</sup> )	MOR (daN/cm <sup>2</sup> )	Shear strength (daN/cm <sup>2</sup> )
Pine	Solid	0.71 ± 0.01	11.12 ± 0.50	106,263 ± 2,895	743 ± 11	140.0 ± 6.0
	Tannin	0.65 ± 0.02	12.40 ± 0.27	81,775 ± 3836	421 ± 174	58.2 ± 40.5
	MDI	0.60 ± 0.02	12.97 ± 0.56	81,170 ± 3,428	519 ± 43	89.8 ± 37.6
Jabon	Solid	0.43 ± 0.05	12.44 ± 0.50	81,394 ± 2,391	548 ± 67	56.7 ± 3.5
	Tannin	0.37 ± 0.02	12.75 ± 0.04	47,488 ± 3,419	241 ± 37	52.7 ± 8.9
	MDI	0.47 ± 0.04	11.83 ± 0.21	52,958 ± 16,126	257 ± 157	46.9 ± 17.5
Sengon	Solid	0.32 ± 0.01	10.38 ± 2.07	57,809 ± 9,088	301 ± 6	53.9 ± 5.6
	Tannin	0.29 ± 0.01	12.40 ± 0.27	49,899 ± 2,518	194 ± 42	55.1 ± 12.3
	MDI	0.27 ± 0.02	12.62 ± 0.18	42,451 ± 4,648	200 ± 36	47.2 ± 18.4
JAS standard			Max 15	Min 75,000	Min 300	Min 54

**Table 3.** Student's *t*-Test for Solid Wood and Glulam

Parameter	Treatment	Mean ± STD	<i>P</i> value	Remarks
Density (g/cm <sup>3</sup> )	Solid	0.49 ± 0.17	0.518	NS
	Glulam	0.44 ± 0.15		
Moisture content (%)	Solid	11.13 ± 1.43	0.042	*
	Glulam	12.49 ± 0.45		
MOE (daN/cm <sup>2</sup> )	Solid	81,822 ± 21,552	0.003	**
	Glulam	59,290 ± 17,588		
MOR (daN/cm <sup>2</sup> )	Solid	531 ± 195	0.007	**
	Glulam	305 ± 151		
Shear strength (daN/cm <sup>2</sup> )	Solid	83.5 ± 42.6	0.131	NS
	Glulam	58.3 ± 26.3		

\*Significant ( $P < 0.05$ ); \*\*Very significant ( $P < 0.01$ ); NS = Not significant

**Table 4.** ANOVA of the Physical and Mechanical Properties of Glulam

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

\*\*Very significant ( $P < 0.01$ )

NS = Not significant

## Mechanical Properties of Glulam

### *Modulus of elasticity*

The MOE values of solid wood and glulam are shown in Table 2. According to Student's *t*-test, shown in Table 3, the MOE of glulam was significantly lower than that of solid wood, which was due to the density of glulam ( $0.44 \text{ g/cm}^3$ ), being lower than that of the solid wood ( $0.49 \text{ g/cm}^3$ ). All wood came from fast-growing species and contained a high proportion of sapwood. Further, the lumber came from many logs, resulting in the variation in density being quite high, even for samples from the same wood species.

Pine glulam and solid pine wood had the highest MOE values, followed by jabon and sengon. Therefore, the pine glulam fulfilled JAS 234-2003 (2003). The type of wood affected the MOE of glulam, as shown by the analysis of variance (Table 4), but the type of adhesive did not. According to Duncan's multi-range test (Table 5), the MOE of pine glulam was significantly different from the MOEs of sengon and jabon glulams, which did not differ from each other. This result is related to the density of each glulam (pine,  $0.63 \text{ g/cm}^3$ ; jabon,  $0.42 \text{ g/cm}^3$ ; and sengon,  $0.28 \text{ g/cm}^3$ ). These results were similar to those reported by Hadi *et al.* (2013), who found that a lower wood density yielded lower mechanical property values. Furthermore, the type of adhesive did not affect MOE, suggesting that the bonding quality of tannin adhesive was not different from that of MDI.

### *Modulus of rupture*

The MOR values for solid wood and glulam are shown in Table 2. The MOR of glulam was significantly lower than that of solid wood, as shown by Student's *t*-test (Table 3). This result was similar to the result for the MOE values of glulam and solid wood. Pine glulam and solid pine wood also had the highest MOR and fulfilled JAS 234-2003 (2003; more than  $75,000 \text{ daN/cm}^2$ ). The type of wood affected the MOR value of glulam, while the type of adhesive did not, based on the analysis of variance presented in Table 4. Duncan's multi-range test shown in Table 5 also indicated that the MOR of pine glulam was significantly different from that of sengon and jabon glulam, which did not differ from each other. As with the MOE, density also affected the MOR of glulam. Higher density glulam had higher MOE and MOR values as noted by Bowyer *et al.* (2003); a wood species with a high density tends to have higher strength because the density and bending strength of a material are proportional.

**Table 5.** Duncan's Multi-range Test for Physical and Mechanical Properties

Wood species	Density ( $\text{g/cm}^3$ )	MOE ( $\text{daN/cm}^2$ )	MOR ( $\text{daN/cm}^2$ )	Hot-water delamination (%)
Pine	0.63 c*	81,472 b	469.91 b	31.82 b
Jabon	0.42 b	50,223 a	248.77 a	10.01 a
Sengon	0.28 a	46,174 a	197.25 a	0.00 a

\*Values followed by the same letters within a column are not significantly different

### Shear strength

The shear strength is the main benchmark for analyzing the quality of gluing. Table 2 shows that pine glulam had the highest shear strength, followed by jabon and sengon. Pine and sengon glulams using mahogany tannin adhesive fulfilled the JAS standard, with a shear strength of more than 54 daN/cm<sup>2</sup>, while among the glulams using MDI adhesive, only pine glulam met the standard. Pine is a softwood, and softwood enables the adhesion process better than hardwood because it has simpler anatomical characteristics. Jabon and sengon are hardwoods, but sengon has a lower density; therefore, adhesion with sengon was easier than with jabon.

According to Student's *t*-test (Table 3), the shear strength of solid wood was not different from that of the glulam, indicating that the adhesion quality was adequate. However, a higher shear strength of glulam could be achieved through greater glue spread, as done by Komariah *et al.* (2015), as well as a higher resin content of mahogany resin. The other results from the analysis of variance (Table 4) indicated that the type of wood and the type of adhesive in glulam did not affect the shear strength, indicating that the adhesion quality of mahogany tannin extract was not different from MDI adhesives.

### Delamination Test

The results of cold-water delamination shown in Table 6 indicate that pine glulam with tannin and MDI adhesives had the highest ratio of delamination, followed by jabon. Glulam made from sengon had no delamination, because sengon has low density and the glue could penetrate more than pine and jabon. According to JAS 234-2003 (2003), sengon and jabon glulams fulfilled the Japanese standard of less than 5% delamination.

In the hot-water delamination test, pine glulam with the tannin adhesive had the highest delamination value, and jabon glulam with MDI adhesive had the highest delamination value compared to other glulams. However, jabon glulam still fulfilled the JAS 234-2003 (2003) requirement of less than 10% delamination. As in the cold-water test, sengon glulam showed no delamination. For exterior use, the sengon and jabon glulams fulfilled JAS standards for both cold-water (maximum 5%) and hot-water conditions (maximum 10%). This result was similar to Amelia *et al.* (2014) mentioning that tannin adhesive from Barbatimão using for plywood had a good performance in both humid and dry environments.

**Table 6.** Glulam Delamination Test

Wood species	Adhesive	Delamination ratio (%)	
		Cold water	Hot water
Pine	Tannin	29.9 ± 30.2	61.3 ± 35.5
	MDI	1.9 ± 3.3	2.4 ± 2.3
Jabon	Tannin	1.5 ± 2.6	17.3 ± 5.9
	MDI	1.3 ± 2.1	2.8 ± 4.8
Sengon	Tannin	0.0 ± 0.0	0.0 ± 0.0
	MDI	0.0 ± 0.0	0.0 ± 0.0
JAS standard		Max 5	Max 10

With respect to glulam properties and the analysis of variance in Table 4, in terms of shear strength, cold-water delamination, MOE, and MOR, the adhesion quality of tannin adhesive was no different from that of MDI. These findings indicate that tannin adhesive from mahogany bark can be used for further applications. To achieve better glulam mechanical properties and better adhesion quality, glue spread should be increased as done by Komariah *et al.* (2015), where 280 g/m<sup>2</sup> glue spread for sengon with MDI glue resulted in MOE and MOR values approximately 1.5 times greater than the present results. In addition, the resin content of the mahogany tannin glue should be much higher than 10%.

### Formaldehyde Emissions

Formaldehyde emissions occur because of unreacted formaldehyde in the resin that is released into the environment, resulting in adverse health effects for people who are exposed. Formaldehyde emissions at certain levels cause various health problems such as a burning sensation to the eyes, nose, and lungs, dizziness, and vomiting (Roffael 1993; ATSDR 2008). Table 7 shows that formaldehyde emissions of jabon and sengon glulams could be classified as F\*\*\*, and pine glulam could be classified as F\*\*\*\*, the lowest emissions and the best class according to JAS 234-2003 (2003).

**Table 7.** Formaldehyde Emissions from Glulam

Wood species	Formaldehyde emissions (mg/L)	Grade*
Pine	0.05	F****
Jabon	0.68	F***
Sengon	0.74	F***

\*Categorized by JAS 234-2003 (2003)

### CONCLUSIONS

1. Glulam constructed from the wood of fast-growing species and mahogany tannin adhesive was no different from solid wood of the same species in terms of density and shear strength.
2. With respect to JAS 234-2003 (2003), pine glulam fulfilled the standards for MOR and MOE, because pine had a high density. While sengon glulam fulfilled the shear strength standard and in delamination tests, the glulam was resistant to cold- and hot-water immersions because sengon had a low density, resulting better glue penetration.
3. All glulams had low formaldehyde emissions. Jabon and sengon glulams were classified as F\*\*\* and pine glulam was classified as F\*\*\*\* for formaldehyde emissions according to JAS 234-2003 (2003).
4. Overall, the results indicated that the adhesion quality of tannin adhesive from mahogany bark is the same as MDI for glulam manufacturing.

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