PHYSICAL AND MECHANICAL PROPERTIES OF GLUED–LAMINATED LUMBER FROM FAST-GROWING TREE SPECIES USING MAHOGANY TANNIN ADHESIVE

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Abstract. Tannin from mahogany bark extract contains polyphenols that could be used in adhesives. In this study, tannin (T) was reacted with resorcinol (R) and formaldehyde (F) at a ratio of 100:3:5 (w/w/w) under alkaline conditions to make an adhesive. The physical–chemical properties of tannin and TRF adhesive were assessed. Three-layer glued–laminated lumber (glulam) made with wood from jabon (*Anthocephalus cadamba*), pine (*Pinus merkusii*), and sengon (*Falcataria moluccana*) was bonded using TRF with a glue spread of 280 g/m^2, cold pressed at 1.47 MPa for 4 h, and then clamped for 24 h. Glulam physical–mechanical properties were tested based on Japanese Agricultural Standard (JAS) 234-2007. Comparison of the physical properties of mahogany tannin and TRF showed that the solids content of mahogany tannin increased after becoming TRF. Compared with phenol resorcinol formaldehyde (PRF) resins, TRF had a similar appearance and specific gravity, but differed in solids content, viscosity, and gel time. Matrix-assisted laser desorption/ionization (MALDI)-time of flight mass (TOF) spectra revealed that mahogany tannin could be classified as hydrolyzable, and pyrolysis Gas Chromatograph-Mass Spectroscopy (GC-MS) showed that the phenolic content was 8.87%. Copolymerization in TRF was indicated by a shift in wave number in Fourier transform IR, reduced percentage of the phenolic component, and increased pH and melting temperature. Mahogany tannin could be prepared for cold-set TRF glulam adhesive, and all glulams fulfilled JAS 234-2007 with regard to MC and MOR. Although TRF adhesive contained a small amount of resorcinol, it was suitable for low density wood, and in dry condition performed equal to PRF.

Keywords: Mahogany tannin, hydrolyzable tannin, tannin resorcinol formaldehyde, glued-laminated lumber (glulam), fast-growing tree species.

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INTRODUCTION

Indonesian log production reached 37.5 million m^3 in 2016, and 85% of the harvested wood was from plantation forests, which are dominated by fast-growing tree species (Ministry of Environment and Forestry 2017). Fast-growing species such as jabon (*Anthocephalus cadamba*), pine (*P. merkusii*), and sengon (*Falcataria moluccana*), with a cutting cycle of 5-10 yr and a diameter less than 30 cm (Hadi et al 2013, 2015), have a greater proportion of sapwood than heartwood (Fajriani et al 2013). According to Clark et al (2006), sapwood has a lower density, MOE, and MOR; however, wood used as a structural material is required to have high strength at large dimensions. One way to increase the use of fast-growing tree species is to make composite products such as glued–laminated lumber (glulam) (Karlinasari et al 2012; Hadi et al 2016).

In glulam manufacturing, the adhesive plays an important role in achieving a satisfactory product (Hendrik et al 2016). The timber industry has until now used commercial wood adhesives based on isocyanate, phenol resorcinol formaldehyde (PRF), polyurethane, phenol formaldehyde, urea formaldehyde resins, and other chemicals. These adhesives are made from synthetic raw materials, which are expensive and often increase in price from year to year (Santoso et al 2014). A bio-adhesive is a type of wood adhesive made from renewable resource materials, and it can be used as a substitute for synthetic adhesives (Moubarik et al 2010). The advantages of using a bio-adhesive include it being a renewable resource and having a more economical price than synthetic adhesives (Lestari et al 2015).

Tannin is a natural polyphenolic compound that can be obtained from trees, primarily through extraction from wood bark (Yi 2016). Some research on tannin as a natural adhesive using extracts derived from pine (*P. merkusii*), mangrove (*Rhizophora* sp.), and mangium (*Acacia mangium*) has been carried out in the past (Pizzi 1982; Santoso 2003). Financially, the production of tannin adhesives is quite feasible, and the use of tannin as a raw material in adhesives can reduce the need for phenolic compounds and formaldehyde by up to 84% and 51%, respectively (Santoso 2001). Moreover, in the studies by Santoso et al (2014, 2016), merbau (*Intsia bijuga*) tannin extract was reacted with resorcinol and formaldehyde to produce a tannin (T) resorcinol (R) formaldehyde (F) adhesive, which was equal in quality to PRF synthetic adhesives. Another tree that potentially has a high tannin content is mahogany (*Swietenia* sp.).

In Indonesia, mahogany wood is usually used to create fine furniture that is strong and has a beautiful appearance (Lestari et al 2018). Demand for mahogany wood is increasing. Mahogany trees are easy to adapt and grow, making them a good candidate for timber production and regeneration of forests in the tropics, including Indonesia (Falah et al 2008). Along with the increased use of mahogany wood, however, the waste of bark is also increasing because the use of mahogany bark has not yet been optimized.

In this study, tannin extracted from mahogany bark was copolymerized with resorcinol and formaldehyde to produce a TRF adhesive. The goal of this research was to investigate the potential use of mahogany bark extract in natural adhesives (bio-adhesives) and to test the effectiveness of the adhesive in glulam manufacture made from fast-growing tree species.

MATERIALS AND METHODS

Adhesive Preparation

The mahogany bark was obtained from trees from the people's plantation forest in Ujung Genteng, Sukabumi, West Java, Indonesia. The trees were approximately 15 yr at harvest. Bark was made into chips that were approximately 2 cm by 3 cm by 0.5 cm in width, length, and thickness, respectively, before being air-dried. The air-dried chips were mixed with water in a 1:4 ratio (w/w) and boiled at 100°C for 3 h. The mixture was filtered to remove the chips, and a portion of the resulting tannin liquid was made into tannin powder by using a spray dryer (Type 190, BÜchi [Switzerland]) at 60°C. The tannin powder was then added to a tannin solution at a 1:3 ratio

(w/w), to produce the tannin for TRF adhesive. Tannin was mixed with resorcinol at a weight ratio of 100:3, respectively, and 40% NaOH was added to adjust the pH to 11. The mixture was then added to 37% formaldehyde as the cross-linker at 100:5 (w/w) and mixed until homogenized. Afterward, the mixture underwent a 1-h conditioning period.

Physical and Chemical Analysis of Tannin and TRF

The physical properties of tannin and TRF liquid were solid content, based on Indonesian National Standard SNI-06-4565-1998 (National Standardization Agency of Indonesia 1998) and calculated using Eq 1; viscosity, using electric viscometer UV-50; density, using pycnometer (50 mL); and visual aspect, based on SNI-06-4565-1998. In addition, the physical properties of TRF were compared with PRF system 1711 adhesive (Akzonobel 2017).

$$\text{Solid Content}\,(\%) = \frac{\text{Oven dry tannin}\,(\text{g})}{\text{tannin liquid}\,(\text{g})} \times 100 \quad (1)$$

The chemical properties of tannin and TRF, including pH, were measured using Fourier transform IR (FTIR) spectrophotometry (using IRPrestige-21; Shimadzu [Japan]), X-ray diffraction (using XRD-7000; Shimadzu), pyrolysis gas chromatography mass spectrometry (using Py-GCMS-QPXP-2010; Shimadzu), MALDI-TOF spectra (using Shimadzu Biotech Axima Performance 2.9.3.20110624), and differential scanning calorimetry (using Jade DSC Perkin Elmer [Boston, USA]).

Glulam Manufacturing

Glulam was made from jabon wood, sengon wood, and pine wood from Ciampea, Bogor, West Java, Indonesia. Each log had a diameter of around 20 cm and was cut into laminas with dimensions of 1 cm × 6 cm × 100 cm (thickness, width, and length, respectively). Three laminas of the same species were bonded with TRF adhesive with a glue spread of 280 g/m^2, followed by cold pressing (specific pressure 1.47 MPa) for 3 h and clamping for 24 h. The same process was used to produce glulams with PRF adhesive for comparison. The three-layer glulams (3 cm × 6 cm × 100 cm; thickness, width, and length, respectively) were conditioned for a month before the test. Seven replications were made for glulam of each combination of wood species and adhesives.

Physical and Mechanical Properties of Glulam and Solid Wood

Glulam physical properties were assessed based on density and MC. The mechanical properties that were tested included shear strength in dry and wet conditions, wood failure in dry and wet conditions, MOE, and MOR according to Japanese Agricultural Standard (JAS) 234-2007. Before the testing of shear strength and wood failure in the wet condition, the glulams were immersed in water at 60°C for 3 h. The mechanical tests were performed using a universal testing machine (Shimadzu UH-100A).

Physical properties of solid wood include density and MC and mechanical properties include shear strength in dry condition, MOE, and MOR. The size of the specimen and testing procedure for physical and mechanical properties of solid wood were according to JAS 234-2007. The results are shown in Table 1 and are used for comparison with the physical and mechanical properties of glulam.

Data Analysis

The comparisons of physical–mechanical properties for glulam vs solid wood and for TRF glulam vs PRF glulam from low-density wood were analyzed using Student's *t*-test. Furthermore, for the data analysis of glulam, a factorial 3 × 3 completely randomized design was undertaken. The first factor was wood species (jabon, sengon, and pine), and the second factor was the type of material (TRF, PRF, and no

Table 1. Physical and mechanical properties of solid wood.

	Physical		Mechanical		
Wood species	Density (g/cm^3)	MC (%)	Shear strength dry (MPa)	MOE × 1000 (MPa)	MOR (MPa)
Jabon	0.34 (0.02)	10.72 (0.38)	5.97 (0.95)	4.56 (0.40)	40.87 (2.65)
Sengon	0.34 (0.03)	10.30 (0.66)	3.87 (0.33)	5.19 (0.32)	44.98 (3.43)
Pine	0.63 (0.03)	12.07 (0.40)	11.40 (0.58)	6.57 (0.98)	85.85 (4.12)
JAS 234-2007		Max 15	Min 5.3	Min 7.3	Min 29.4

Values in parentheses are standard deviations.

adhesive in the case of solid wood). If the analysis of variance revealed that a treatment factor was significantly different ($p \leq 0.05$), Duncan's multirange test was used for further analysis.

RESULTS AND DISCUSSION

Physical Properties of Tannin and TRF

The tannin was a liquid with a red-brown color and a solid content of 17.65%, with very low viscosity. As shown in Table 2, the appearance and specific gravity of TRF were similar to those of PRF resin, but there were some differences in solids content, viscosity, and gel time. These differences were likely a result of the different raw material used. This result was similar to that of previous research on merbau wood liquid extract as an adhesive component (Santoso et al 2014).

Chemical Properties of Tannin

Tannin had a pH of 6. Results from FTIR (Fig 1) revealed that the functional groups of tannin included a hydroxyl group based on wave number 3335 cm^{-1}, a carbonyl group based on wave number 1734 cm^{-1}, an aromatic ring vibration based on wave number 1518 cm^{-1}, and an aromatic alkane ring based on wave number 1357 cm^{-1}. These results indicated that the tannin contained functional groups similar to those in tannic acid (Hindriani 2005) and mahogany bark extract (Lestari et al 2015).

MALDI-TOF spectra in Fig 2 show that the chemical compounds in tannin include ellagic acid + COO + gallic acid. Thus, the following equation was used to construct Table 3: M + $Na^+ = 23\ (Na^+) + 304 + 1H$ (ellagic unit) + 152 (gallic unit) + 44 (COO), and all subsequent peaks were formed because of the addition of further gallic acid units. Moreover, the results from py-GCMS, shown in Fig 3, indicated that tannin contains 5.22% methanamide based on the retention time of 3.451 min, 13.51% ethylic acid based on the retention time of 5.949 min, 14.26% palmitic acid based on the retention time of 20.945 min, 3.19% phenol, 2-methoxy-guaiacol based on the retention time of 13.506 min, 3.64%

Table 2. Physical properties of TRF and PRF adhesives.

Properties	TRF	PRF[a]
Appearance		
Phase	Liquid	Liquid
Color	Dark brown	Reddish brown
Smell	Phenol	Phenol
Viscosity (centipoise)	130	3000
Specific gravity	1.10	1.15
Solid content (%)	21.73	54-58
Gel time (min)	120	25

PRF, phenol resorcinol formaldehyde; TRF, tannin resorcinol formaldehyde.
[a] Akzonobel (2017).

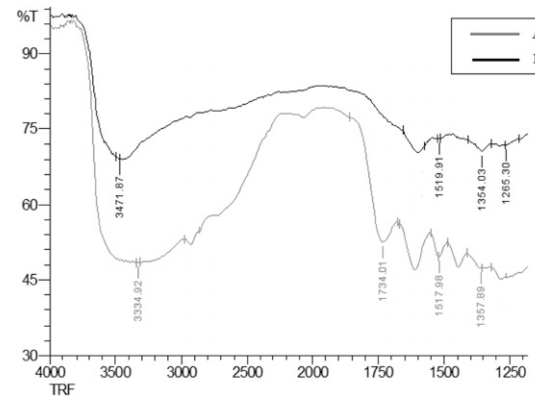

Figure 1. Spectograph of (a) tannin extract and (b) tannin (T) resorcinol (R) formaldehyde (F) adhesive.

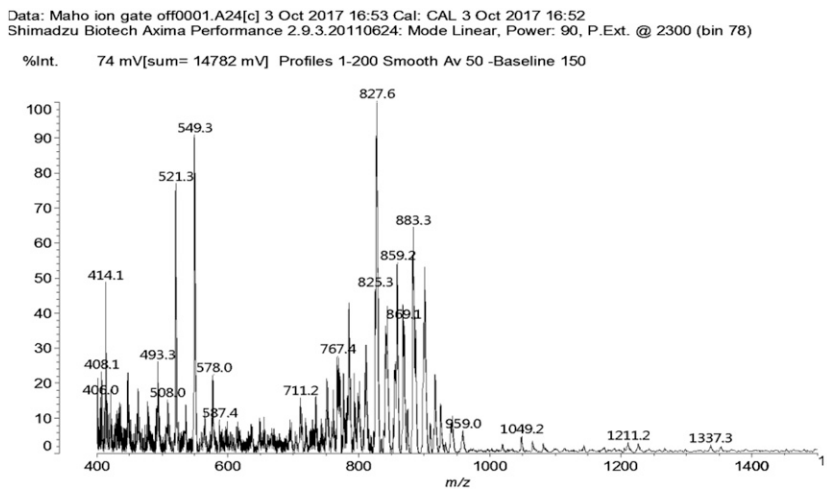

Figure 2. The MALDI-TOF spectra of mahogany tannin extract.

1,2 benzenediol based on the retention time of 16.221 min, and 2.04% 2,6-dimethoxyphenol based on the retention time of 16.417 min. Most of the peaks in the MALDI-TOF spectra and the compounds shown by py-GCMS indicated that mahogany tannin is a hydrolyzable tannin with a total proportion of phenolic compounds of 8.87%. This total proportion of phenolic compounds was similar to that of merbau tannin, as reported by Santoso et al (2014), suggesting that it had potential for use as an adhesive. Moreover, Santos et al (2016) and Ghahri and Pizzi (2018) reported that hydrolyzable tannin could be successfully used as a wood adhesive.

Tannin next underwent thermal analysis with DSC, and the results are presented in Fig 4(a). Thermal analysis using DSC is intended to understand the behavior of polymers when heated. The results showed that a point transition phase occurred at 95.92°C, indicating a solid phase change of the tannin, which became soft and melted, as shown by an endothermic peak.

Chemical Properties of TRF

TRF had a pH of 11, whereas PRF had a pH of 8. Based on FTIR results (Fig 1), the functional groups of TRF adhesive showed shifts in wave numbers compared with tannin. The intensities of the hydroxyl group and aromatic alkane ring group were decreased, with the peaks shifting to 3472 cm^{-1} and 1354 cm^{-1}. The intensity of the aromatic ring vibration group was increased, with a wave number of 1520 cm^{-1}. In addition, the TRF had an ether group, which was marked by a wave at 1283 cm^{-1}. These absorption shifts were similar to those reported in previous research and indicated a reaction between tannins, resorcinol, and formaldehyde to form TRF (Rachmawaty 2017).

After the addition of resorcinol and formaldehyde, the TRF assessment with py-GCMS (Fig 5) showed that the concentration of phenol 2-methoxy-guaiacol decreased to 0.49% (retention time 13.934 min), the concentration of 2,6-dimethoxyphenol decreased to

Table 3. Dominant oligomer MALDI-TOF peaks and description of structures present in the mahogany tannin extract.

Calculated M + Na^+	Experimental M + Na^+	Description M + Na^+
522	521.3	Ellagic acid + COO + 1 gallic acid
674	669.7	Ellagic acid + COO + 2 gallic acid
825	827.6	Ellagic acid + COO + 3 gallic acid
978	975.3	Ellagic acid + COO + 4 gallic acid

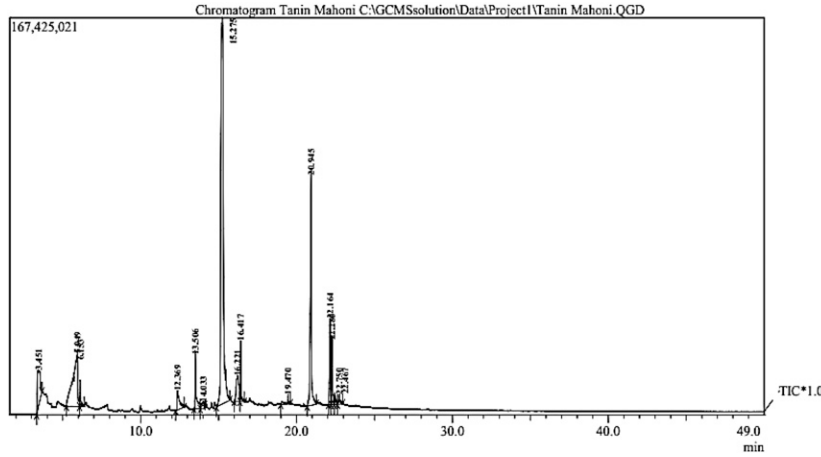

Figure 3. Chromatogram of tannin extract.

0.43% (retention time 16.574 min), and a new compound, dimethylamine, formed and had a concentration of 96.12% (retention time 3.686 min). These results indicated that copolymerization occurred between tannin, resorcinol, and formaldehyde.

Thermal analysis using DSC of TRF adhesive is shown in Fig 4(b). The point transition phase increased after copolymerization, becoming 117.07°C. These results were higher than those obtained in previous studies on the synthesis of tannin formaldehyde adhesives from *Acacia dealbata* bark of 110.74°C (Lisperguer et al 2016) and TRF from *A. mangium* extract bark of 98.73°C (Rachmawaty 2017).

Physical Properties of Glulam

Density. The density values of glulam and solid wood are shown in Table 4. Glulam and solid pine wood had the highest densities (0.59 g/cm^3-0.63 g/cm^3), followed by sengon wood (0.34 g/cm^3-0.37 g/cm^3) and jabon wood (0.34 g/cm^3-0.36 g/cm^3). This research used both low-density wood (sengon and jabon woods) and medium-density wood (pine wood). The results from Student's *t*-test in Table 5 showed no significant difference between the density of glulam and that of solid wood from the same species. These findings indicate that the glue line and the pressure in the manufacturing process did not affect the density of the glulam (Lestari et al 2015). The

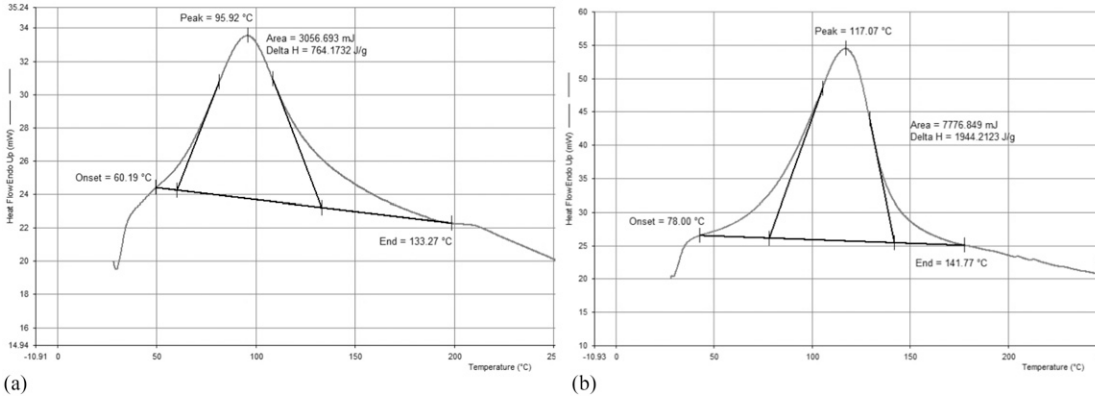

Figure 4. Differential scanning calorimetry of (a) tannin extract (b) tannin resorcinol formaldehyde adhesive.

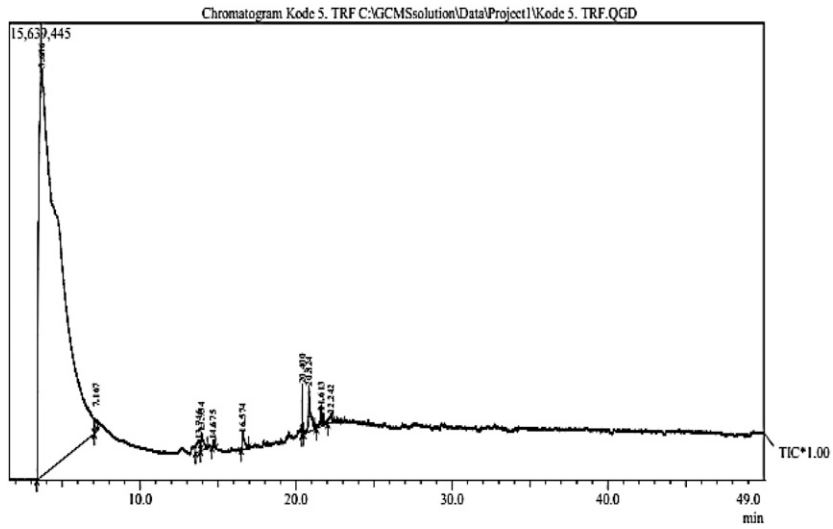

Figure 5. Chromatogram of tannin resorcinol formaldehyde (TRF).

glue line was very thin with no weight gain effect, and pressure was applied with the same value.

According to the variance analysis of glulam in Table 6, the wood species significantly affected the density, with sengon and jabon woods having a low density but pine wood having a medium density. The TRF and PRF adhesives did not significantly affect the density because both adhesives were applied using the same glue spread.

MC. MC is an important factor in a glulam manufacturing. A high MC would inhibit the adhesive from getting into the wood and affect the penetration of the adhesive (Ruhendi et al 2007). According to Table 4, all glulams and solid wood of the same species had moisture contents ranging from 10.30% to 12.07%. These values fulfilled the JAS 234-2007, which requires a MC lower than 15%. The moisture contents of glulam and solid wood were not significantly different according to Student's *t*-test in Table 5, indicating that both lumbers approached the EMC in Bogor (10.9-20%).

According to the analysis of variance presented in Table 6, the MC of glulam was affected by wood species and the interaction of both wood species and type of adhesive. Pine wood had the highest value for MC, whereas sengon and jabon woods had lower moisture contents, which did not differ from each other (Table 7). Pine wood with its higher density had a thicker cell wall, permitting it to retain water more than sengon and jabon

Table 4. Physical and mechanical properties of glulam and solid wood.

Wood species	Type of material	Physical		Mechanical					
				Shear strength (MPa)		Wood failure (%)		MOE × 1000 (MPa)	MOR (MPa)
		Density (g/cm^3)	MC (%)	Dry	Wet	Dry	Wet		
Jabon	TRF	0.36 (0.02)	10.87 (0.32)	4.27 (0.72)	0.99 (0.06)	67.14 (7.56)	0.00 (0.00)	4.51 (0.47)	42.04 (1.37)
	PRF	0.36 (0.02)	10.37 (0.37)	3.92 (0.53)	5.01 (0.41)	84.28 (11.34)	85.14 (14.44)	4.85 (0.51)	43.32 (2.25)
Sengon	TRF	0.37 (0.02)	10.67 (0.60)	3.64 (0.28)	0.85 (0.09)	89.71 (13.92)	0.28 (0.09)	5.53 (0.38)	48.71 (3.14)
	PRF	0.36 (0.02)	10.87 (0.61)	4.21 (0.37)	3.44 (0.39)	98.57 (3.78)	93.43 (6.27)	5.45 (0.22)	44.59 (2.55)
Pine	TRF	0.59 (0.01)	11.58 (0.38)	2.31 (0.44)	1.41 (0.11)	24.00 (7.21)	4.28 (0.95)	3.69 (0.27)	57.43 (4.61)
	PRF	0.63 (0.04)	11.53 (0.65)	7.00 (0.77)	5.22 (0.40)	84.29 (9.76)	75.00 (7.64)	4.49 (0.53)	60.56 (4.41)
JAS 234-2007		—	Max 15	Min 5.3	—	—	—	Min 7.3	Min 29.4

PRF, phenol resorcinol formaldehyde; TRF, tannin resorcinol formaldehyde. Values in parentheses are standard deviations.

Table 5. Student's *t*-test of solid wood and glulam.

Parameter	Treatment	Mean	*p*-value	Remarks
Density (g/cm^3)	Solid	0.44 (0.14)	0.82	NS
	Glulam	0.44 (0.12)		
MC (%)	Solid	11.03 (0.91)	0.82	NS
	Glulam	10.98 (0. 65)		
Shear strength, dry (MPa)	Solid	7.06 (3.33)	0.00	**
	Glulam	4.21 (2.0)		
MOE (MPa)	Solid	5441 (1052)	0.01	**
	Glulam	4754 (776)		
MOR (MPa)	Solid	57 (21)	0.12	NS
	Glulam	50 (8)		

NS = not significantly different. Values in parentheses are standard deviations. **Very significantly different ($p \leq 0.01$).

woods. This outcome was similar for the MC of mangium wood described by Komariah et al (2015). In that study, mangium had the highest density (0.53 g/cm^3) compared with manii (0.39 g/cm^3) and sengon (0.27 g/cm^3), and it had the highest MC.

Mechanical Properties of Glulam

Shear strength and wood failure. Shear strength in the dry condition (Table 4) showed that glulam made from sengon and jabon woods using TRF had a higher shear strength value (3.64 MPa and 4.27 MPa, respectively) than pine wood (2.31 MPa). Pine wood had lower wood failure in the dry condition than sengon and jabon woods (as seen in Fig 6). The same result was reported by Alamsyah et al (2007); glulam from pine wood and *A. mangium* (density 0.55 g/cm^3) had lower wood failure then glulam made from sengon wood. This outcome indicated that the TRF adhesive is more suitable with low-density wood than high-density wood, with sengon and jabon wood having lower density (0.34 g/cm^3) than pine wood (0.59 g/cm^3). This result may also indicate that the low viscosity of the TRF resin possibly causes problems in remaining on the surface of a higher density wood and that it penetrates less. Meanwhile, pine glulam using PRF and its solid wood fulfilled the JAS 234-2007 standard. The result of the Student's *t*-test (Table 5) showed that the shear strength under dry glulam conditions was very significantly different from that of solid wood, at only 60% of that of solid wood. This result showed that the quality of glulam was not as good as that of solid wood.

According to the variance analysis of the glulam prepared under dry conditions (Table 6), wood species, type of material, and their interaction vary significantly and are affected by the shear strength and wood failure values. Duncan's multirange test among wood species under dry conditions (Table 7) showed that pine wood had the highest shear strength, followed by jabon and sengon. Solid pine wood had higher mechanical properties than sengon and jabon woods, with the

Table 6. Analysis of variance of glulam.

Parameter	Wood (A)	Type of material (B)	Interaction (A × B)
Density (g/cm^3)	**	NS	**
MC (%)	**	NS	*
Shear strength, dry (MPa)	**	**	**
Shear strength, wet (MPa)	**	**	**
Wood failure, dry (%)	**	**	**
Wood failure, wet (%)	*	**	**
MOE (MPa)	**	**	**
MOR (MPa)	**	**	**

NS, not significantly different. *Significantly different ($p \leq 0.05$). **Very significantly different ($p \leq 0.01$).

Table 7. Duncan's multirange test of wood species.

Wood species	Density (g/cm^3)	MC (%)	Shear strength (MPa)		Wood failure (%)		MOE (MPa)	MOR (MPa)
			Dry	Wet	Dry	Wet		
Jabon	0.3571 a[a]	10.651 a	4.72 b	3.00 b	75.71 b	42.57 ab	4642 a	42 a
Sengon	0.3543 a	10.610 a	3.90 a	2.42 a	94.14 a	46.86 b	5392 b	46 b
Pinus	0.6138 b	11.727 b	6.91 c	3.32 c	54.14 c	39.64 a	4916 a	68 c

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

shear strength of pine wood being higher than those of the other two wood species. Meanwhile, wood failure of pine wood was lower than sengon and jabon woods. Pine wood had a higher density (0.63 g/cm^3) than sengon (0.34 g/cm^3) and jabon (0.34 g/cm^3) woods, which caused the gluing quality of pine wood to be lower than those of sengon and jabon woods.

By contrast, the shear strength of glulam using a TRF adhesive under wet conditions was lower than that of glulam using a PRF (Table 4) adhesive. Moreover, the percentage of wood failure in the wet condition for all TRF glulams was lower than for all PRF glulams. The tannin in the TRF is a hydrolyzable tannin that can be dissolved in water, whereas synthetic phenol in PRF is difficult to dissolve in water. In the analysis of variance (Table 6), the shear strengths of different glulams under wet conditions was very significantly affected by wood species, type of material, and their interaction. Conversely, wood failure under wet conditions was significantly affected by wood species and very significantly affected by the type of material and the interaction of these two factors. Duncan's multirange test of wood species (Table 7) showed that the three types of wood were significantly different from each other, with sengon having the lowest shear strength in the wet condition, followed by jabon and pine. This result was similar to that in previous research by Santoso et al (2016), who showed that pine glulam using TRF from merbau with a density of 0.54 g/cm^3 had a higher shear strength in the wet condition than Pangsor (*Ficus callosa*) glulam using the same adhesive with a density of 0.33 g/cm^3. Meanwhile, with regard to wood failure in the wet condition, sengon wood had the highest value, although close to jabon wood, with pine wood having the lowest.

MOE. The MOE values (Table 4) showed that glulam from pine wood had the lowest value. Meanwhile, glulam from sengon wood and solid sengon wood had the highest values followed by glulam from jabon wood and solid jabon wood. In the case of pine wood, the solid wood fulfilled the JAS standard, but the glulam did not. According to the Student's *t*-test in Table 5, the MOE value of glulam was very significantly lower than that of solid wood. The same result was reported by

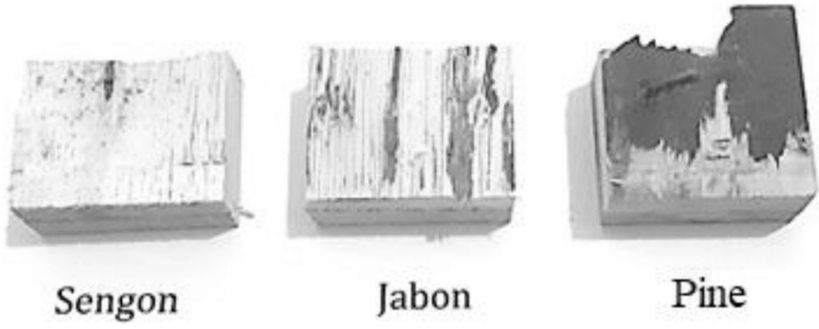

Figure 6. Condition of wood failure of glulam from sengon, jabon, and pine wood using tannin resorcinol formaldehyde adhesive.

Lestari et al (2015), indicating that the density variation among laminas, which came from many logs, and gluing system of glulam did not yield a product as good as solid wood.

The analysis of variance (Table 6) showed that the MOE value between glulams was very significantly affected by wood species, type of material, and their interaction. In the Duncan's multirange test (Table 7), sengon wood had the highest value, followed by pine wood and jabon wood. The adhesion of sengon wood was the best among the three species as indicated by the highest wood failure in the dry condition, which caused the MOE of sengon glulam to be the highest. Furthermore, for the type of material (Table 8), solid wood had the highest value followed by PRF and TRF glulams, which did not differ from each other. This outcome indicated that the gluing system of glulam was under solid wood, meanwhile the adhesive quality of PRF was equal to TRF in the dry condition.

MOR

MOR is a parameter for measuring the bending strength of wood. It equals the magnitude of the load required to cause failure in bending, and is influenced by wood density (Olorunnisola 2018). The MOR values of glulam and solid wood are shown in Table 4. The three wood species (for both glulam and solid wood) fulfilled the JAS standard 234-2007, reaching more than 29.4 MPa. Generally, the MOR of glulam was not significantly different from that of solid wood, as determined by the Student's t-test (Table 5).

The wood species, type of material, and their interaction very significantly affected the MOR according to the analysis of variance (Table 6). Duncan's multirange test in Table 7 showed the wide range of MOR values, as affected by wood species (42 MPa-68 MPa). This result was similar to that of Lestari et al (2015), in which the MOR value was affected by the density of wood. Pine glulam had the highest density, followed by sengon and jabon woods. Meanwhile, Table 8 shows that the MOR values of glulams differed from those of solid wood, with the MOR of glulams reaching 86% of the value for solid wood. Furthermore, MOR values of TRF and PRF glulams were not different from each other. This result indicates that TRF adhesive was equal in quality to the PRF.

Table 8. Duncan's multirange test of the kind of material.

Kind of material	Shear strength dry (MPa)	MOE (MPa)	MOR (MPa)
TRF	3.41 a[a]	4577 a	49 a
PRF	5.05 b	4932 b	49 a
Solid	7.08 c	5440 c	57 b

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

In a more detailed analysis, the Student's *t*-test of TRF vs PRF glulams from low-density wood (Table 9) showed that the MOE, MOR, shear strength, and wood failure under dry conditions of glulam using TRF were not significantly different from the values for glulam using PRF. By contrast, the values for shear strength and wood failure in the wet condition showed that TRF glulam was very significantly different from PRF glulam. As shown in Fig 2, mahogany tannin extract contained carboxylic acid, and according to Fig 5, the TRF adhesive mostly contained dimethylamine, which caused TRF to easily dissolve in water (O'Neil 2001). In summary, the quality of the TRF adhesive was equal to that of PRF for low-density wood under dry conditions, indicating that TRF should only be used for indoor applications.

Regarding the previous discussion, it could be mentioned that eventhough TRF adhesive used a small amount of resorcinol, the resulting TRF adhesive had good quality for glulam adhesive, especially for low density wood. Furthermore, even mahogany tannin contained hydrolizable tannin, but it could have very good performance for interior adhesives.

CONCLUSION

Based on the research presented here, it can be concluded that:

1. Mahogany tannin is a hydrolyzable tannin with a phenolic content of 8.87%, and it could be prepared for cold-set TRF glulam adhesive.
2. The presence of several shifts in the wave numbers, the reduced percentage of phenolic

Table 9. Student's *t*-test of TRF and PRF glulams from low-density wood.

Parameter	Treatment	Mean[a]	*p*-value	Remarks
Shear strength, dry (MPa)	TRF	3.96 (0.62)	0.40	NS
	PRF	3.78 (0.44)		
Shear strength, wet (MPa)	TRF	0.92 (0.10)	0.00	**
	PRF	2.94 (2.18)		
Wood failure, dry (%)	TRF	78.43 (15.91)	0.12	NS
	PRF	87.00 (12.52)		
Wood failure, wet (%)	TRF	0.14 (0.16)	0.00	**
	PRF	42.71 (45.11)		
MOE (MPa)	TRF	5022 (670)	0.56	NS
	PRF	5152 (487)		
MOR (MPa)	TRF	45 (4)	0.28	NS
	PRF	43 (2)		

NS, not significantly different; PRF, phenol resorcinol formaldehyde; TRF, tannin resorcinol formaldehyde. **Very significantly different ($p \leq 0.01$).
[a] Values in parentheses are standard deviations.

compounds, and the increasing pH and melting temperature from mahogany tannin extract to TRF indicated that copolymerization occurred.

3. The solids content of mahogany tannin was increased after becoming TRF. Compared with PRF, TRF had a similar appearance and specific gravity, although some differences in terms of solids content, viscosity, and gel time were present.
4. All glulams fulfilled the JAS for MC and MOR.
5. With regard to glulam properties, even TRF adhesive with small amount of resorcinol was suitable for low-density wood, such as sengon and jabon. The values of MOE, MOR, and shear strength of glulam in the dry condition using TRF were same as that using PRF. In other words, the quality of TRF was equal to PRF for low-density wood in the dry condition.

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