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Performance of Six-Layered Cross Laminated Timber of Fast-Growing Species Glued with Tannin Resorcinol Formaldehyde

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ABSTRACT

The aim of this study were to evaluate tannin resorcinol formaldehyde (TRF) for the preparation of cross-laminated timbers (CLTs) made from fast-growing tree species and to analyze the physical and mechanical properties of CLTs. TRF copolymer resin was prepared by using the bark extracts of *Swietenia mahagoni* (L.) Jacq. It was observed that the TRF adhesive possessed less solid content (23.59%), high viscosity (11.35 poise), and high pH values (10.0) compared to the standard phenol resorcinol formaldehyde. The TRF adhesive was applied to produce CLTs with the addition of 15% tapioca and flour as an extender. The six-layered CLTs were produced from sengon (*Falcataria moluccana* Miq.), jabon [*Anthocephalus cadamba* (Roxb) Miq.], coconut (*Cocos nucifera* L.), and the combination of coconut-jabon and coconut-sengon wood. The analysis of variance revealed that the layer composition of CLT significantly affected the physical and mechanical properties of the beam. While the modulus of rupture met the standard, the moisture content and modulus of elasticity values did not fulfill JAS 1152-2007. All of the CLTs produced in this study demonstrated low formaldehyde emission, ranging from 0.001 mg/L to 0.003 mg/L, thereby satisfying the JAS 1152 for structural glue laminated timber.

Keywords: bio-adhesive, composite product, fast-growing species, structural component, tannin

1. INTRODUCTION

The National Socioeconomic Survey revealed that the housing shortage/backlog in Indonesia increased from 11.4 million houses in 2015 to 12.75 million houses in 2020, while it was targeted to reduce the housing backlog to 5 million in 2024 (MOPWH, 2022). Timber supply for construction materials could, therefore, be expected to increase with the increase in demand for new houses.

Timber consumption at the household level for the construction of roofs and buildings were 0.008 m^3/m^2–0.016 m^3/m^2 and 0.0035 m^3/m^2 – 0.13 m^3/m^2, respectively (Abdulah *et al*., 2020). The study further revealed that solid wood was the most consumed construction material (Abdulah *et al*., 2020). This finding, however,

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imposes insecurity on the forestry sector. Log production from natural and plantation forests was 47.9 million m^3 in 2018 (MOEF, 2020) which declined in 2019 to 45.7 million m^3 (MOEF, 2021).

Fast-growing tree species have the potential to fill the gap in forest production to serve the increasing demand for construction materials. Sengon [*Falcataria moluccana* (Miq.) Barneby & J.W. Grimes], jabon [*Anthocephalus cadamba* (Roxb.) Miq.], and coconut (*Cocos nucifera* L.) are fast-growing species that grow abundantly in Indonesia. Despite their advantages shorter harvest period and larger wood diameter, one of the drawbacks of fast-growing tree species is their small diameter. Engineered wood technology may be used to turn small-diameter logs into large-diameter logs for construction or in structural components.

Cross laminated timber (CLT) is a wood panel product comprising multilayered sawn wood glued perpendicularly. CLT has a high prefabrication rate, is easy to transport and install, and causes less environmental damage. It has tremendous properties of stiffness and strength, making it suitable for construction materials (Barreto *et al*., 2019; Brandner, 2013; Choi *et al*., 2018; Fujimoto *et al*., 2021; Okuda *et al*., 2018; Yang *et al*., 2021). CLTs are also considered an alternative to concrete and steel (Karacabeyli and Douglas, 2013), ultimately aiding in the reduction of greenhouse gas emissions (D'Amico *et al*., 2021; Hindman and Bouldin, 2015).

Commercial synthetic adhesives are applied in the manufacturing process. A wide range of studies has been conducted using numerous adhesives to manufac4

ture CLTs. Phenol resorcinol formaldehyde (PRF) was used to manufacture three-layered batai CLT (Liew and Maining, 2021), hybrid-wooden-laminated timber (Choi *et al*., 2018), and tropical hybrid CLT (Galih *et al*., 2020). The double spread of water-based polymer isocyanate was applied to produce sengon CLT (Apriliana, 2012), resorcinol was used to manufacture domestic larch CLT (Song and Hong, 2016), polyvinyl acetate to bond densified batai CLT (Feng and Chiang, 2020), polyurethane adhesive to manufacture southern pine CLT and mixed Japanese Larch and yellow poplar CLT (Hindman and Bouldin, 2015; Song and Kim, 2022). The primary drawbacks of synthetic adhesives are that they are expensive (Santoso *et al.*, 2014) and pose potential health risks due to their enormous formaldehyde emission (Yauk *et al*., 2020). The development of bio- adhesives produced from renewable resources would aid in the reduction of heath and environmental concerns associated with synthetic adhesives used in engineered wood products (Yauk *et al*., 2020).

Tannins are natural compounds found in several plant families that comprise a large number of phenolic rings (Ramires and Frollini, 2012). It is a polyphenolic biomolecule generally extracted from the bark and wood of trees (Jahanshaei *et al*., 2012). Tannin from chestnut-leaved oak (*Quercus castaneifolia* C.A. Mey) has successfully been used to make ecologically sound particleboard (Jahanshaei *et al*., 2012). Tannins extracted from merbau (*Intsia* spp.), mangium (*Acacia mangium* Willd.), and mahoni [*Swietenia mahagoni* (L.) Jacq.] have been used to adhere engineered products from lignocellulosic materials (Lestari *et al*., 2015; Pari and Santoso, 2019; Rachmawati *et al*., 2018; Santoso *et al*., 2012, 2016). Condensed tannin extracts have previously been demonstrated to be effective phenol substitutes in the production of phenol-formaldehyde resins, resorcinol-formaldehyde resins, and PRF resins (Pizzi, 2018). A more recent study revealed that PRF can additionally be used to manufacture glue laminated timber (Hendrik *et al*., 2019; Lestari *et al*., 2015). It was found that the manufactured glulam satisfied some of the Japan Agricultural Standard JAS 234-2003 for Glue Laminated Timber (JAS, 2003). Although a large amount of studies focus on the on the application of tannin-based adhesive on engineered wood, research on its application on CLT of fast-growing species is still limited.

The aim of this study was to analyze the use of tannin resorcinol formaldehyde (TRF) from *Swietenia mahagoni* (L.) Jacq. bark for the preparation of cross-laminated timber prepared from sengon, jabon, and coconut. These species were selected for their commercial potential and availability. The study further observed the physical and mechanical properties, in addition to the formaldehyde emission of CLT.

2. MATERIALS and METHODS

2.1. Materials

2.1.1. Lumber

Lab-scale CLT was manufactured from sengon [*Falcataria moluccana* (Miq.) Barneby & J.W. Grimes], jabon [*Anthocephalus cadamba* (Roxb.) Miq.], and coconut (*Cocos nucifera* L.) in this study. The wood was collected from West Java, Indonesia, where the dimensions for each lumber used were 1,200 mm (length) × 55 mm (width) × 12 mm (thickness; Fig. 1). The lumber planks were visually selected from any checks and air-dried to a moisture content of 14%.

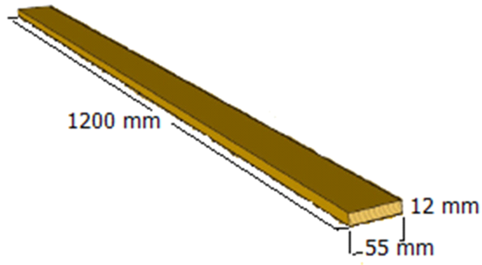

Fig. 1. The dimensions of the lumber.

2.1.2. Adhesive

TRF was used to bind the CLT. An extracted tannin from *Swietenia mahagoni* (L.) Jacq. The bark was then used to formulate TRF. The extract tannin was copolymerized with resorcinol and formaldehyde in accordance with the formula used by Santoso *et al*. (2012). Tapioca and flour were used as extenders, with a ratio of 15%. The portion of resorcinol was 0.25 mole, as suggested in a previous study (Santoso and Abdurachman, 2016).

2.2. Cross laminated timber (CLT) fabrication

The CLT comprised six lumber boards with five different layer compositions: coconut CLT (C), sengon CLT (S), jabon CLT (J), mix coconut and sengon CLT (CS) and mix coconut and jabon CLT (CJ; Table 1).

The lumbers were planed to maintain dimensional consistency and to ensure optimal gluing before lamination (Karacabeyli and Douglas, 2013). They were then thoroughly cleaned. The lumbers were glued with the glue spread of 170 g/m^2 and cold pressed for 24 hours.

Table 1. Layer compositions of CLTs

CLT types	Layer					
	1st	2nd	3rd	4th	5th	6th
Coconut (C)	C	C	C	C	C	C
Sengon (S)	S	S	S	S	S	S
Jabon (J)	J	J	J	J	J	J
Coconut-Sengon (CS)	C	S	C	S	C	S
Coconut-Jabon (CJ)	C	J	C	J	C	J

CLT: cross laminated timber.

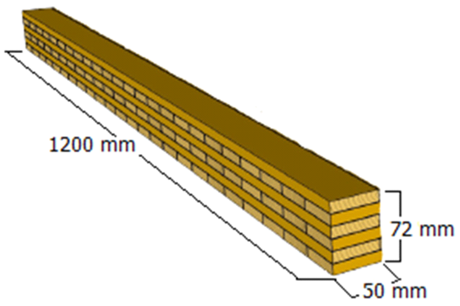

Fig. 2. Manufactured CLT board. CLT: cross laminated timber.

The dimensions of the CLT boards were 1,200 mm × 50 mm × 72 mm (Fig. 2). The six-layered CLTs were then conditioned at ambient temperature for one week before testing to eliminate the excess tensions during the manufacturing of CLT (Fridiyanti and Massijaya, 2018; Prabuningrum *et al*., 2020).

2.3. Physical and chemical properties of tannin resorcinol formaldehyde

The physical and chemical properties of TRF were evaluated in accordance with the Indonesian National Standard SNI 06-4567-1998 (BSN, 1998). The SNI 06-4567-1998 was used in the absence of a TRF standard for plywood adhesive considering TRF has similar characteristics with PRF. The physical properties analyzed included phase, color, odor, and viscosity, while the chemical properties comprised pH, specific gravity, solid content, and free formaldehyde (Table 2).

2.4. Physical properties of cross laminated timber (CLT)

The physical properties of CLT was analyzed as the Indonesian National Standard (SNI) 01-6240-2000 for Laminated Veneer (BSN, 2000). The physical properties tested comprised moisture content (MC) and density.

Table 2. Physical and chemical properties of tannin resorcinol formaldehyde

Properties	TRF
Phase	Liquid
Color	Red-brown
Odour	Phenol
Viscosity, poise	11.35
pH	10.00
Specific gravity	1.07
Solid content (%)	23.59
Free formaldehyde (%)	0.0044

2.4.1. Moisture content

The dimension of the MC sample tests was 50 mm × 50 mm × 50 mm. The air-dried specimens were weighed, after which they were oven dried at 103 ± 2℃ for 24 hours to constant weight. The MC value was determined using Equation (1).

$$MC\ (\%) = (W_1 - W_2) / W_2 \times 100 \tag{1}$$

Where:

W_1 = Initial weight (g)

W_2 = Oven-dried weight (g)

2.4.2. Density

The dimension of the test specimen was 50 mm × 50 mm × 50 mm. The specimens were air-dried and weighed. The volume of test specimens was calculated by multiplying the dimensions of length, width, and thickness. The density was determined using Equation (2).

$$Density\ (g/cm^3) = W_1 / V_1 \tag{2}$$

Where:

W_1 = Initial weight (g)

V_1 = Specimen volume (cm^3)

2.5. Mechanical properties of cross laminated timber (CLT)

The test for the mechanical properties of CLT was performed in accordance with the Japan Agricultural Standard JAS 1152 2007 for structural glued laminated timber (JAS, 2007) and ASTM D-143-94 (ASTM, 2000). The properties examined included shear strength, modulus of elasticity (MOE), and modulus of rupture (MOR).

2.5.1. Shear strength

The CLT specimen was tested under dry and wet conditions. The dimension of the shear strength sample was 50 mm × 50 mm × 65 mm. For the wet test, the test specimens were boiled for four hours, and then oven-dried at 60 ± 3℃ for 20 hours. They were then boiled for another four hours and immersed in distilled water at room temperature for 10 minutes. The dry test was subsequently conducted. Shear testing was performed on a Shimadzu universal testing machine. The shear strength was calculated using Equation (3).

$$\text{Shear strength (kg/cm}^2\text{)} = \text{Maximum load / Shear surface area} \quad (3)$$

2.5.2. Modulus of elasticity (MOE) and modulus of rupture (MOR)

The dimension of the samples was 50 mm × 50 mm × 760 mm and the span length was 710 mm. The MOE and MOR were calculated using Equations (4) and (5).

$$\text{MOE (kg/cm}^2\text{)} = \triangle PL^3 / (4\triangle Ybh^3) \quad (4)$$

$$\text{MOR (kg/cm}^2\text{)} = 3PL / (2bh^2) \quad (5)$$

Where:

△P = Difference between the upper and lower loading limits in the proportional limit region (kg)

△Y = Deflection with respect to △P (cm)

L = Span length (cm)

b = Width of the CLT (cm)

h = Thickness of the CLT (cm)

P = Maximum loading (kg)

2.6. Formaldehyde emission of cross laminated timber (CLT)

The study used the Wilhelm-Klauditz-Institut (WKI) bottle method. The bottle was filled with 25 mL of distilled water above which the specimen with the dimension of 25 mm × 30 mm × 50 mm was suspended. It was then kept in an oven at 40℃ for 24 hours and subsequently stored in a refrigerator at 6℃. The bottle was then carefully removed and the solution was collected for further analysis. A total of 10 mL of the sample solution was placed in a 100 mL Erlenmeyer and mixed with 10 mL of acetylacetone ammonium acetate solution. The solution was then thoroughly stirred. The Erlenmeyer was placed in a water bath at 60℃–65℃ for 10 minutes, and then stored at room temperature. The absorbance of the mixture was analyzed with a spectrophotometer at a wavelength of 412 nm. The absorbance of the mixture was plotted at the calibration curve of the formaldehyde standard solution.

2.7. Data analysis

The data of each test were statistically examined using Minitab Statistical Software version 17. Analysis of variance (ANOVA) was used to examine the effects of the CLT layer compositions on its physical and mechanical properties. The means were then compared using Tukey Range Test when the ANOVA revealed a significant difference between variables to determine which groups were significantly different from others at 95 percent confidence levels. The 95% confidence level was selected primarily considering the 5% threshold in a normal distribution was roughly the second SD away from the mean.

3. RESULTS and DISCUSSION

3.1. Physical and chemical properties of tannin resorcinol formaldehyde

The viscosity of TRF was determined to be higher (11.35 poise) than the PRF standard (3.40 poise; Akzonobel, 2017), TRF from mangium (1.04 poise; Rachmawati *et al*., 2018), TRF extracted from *Acacia mangium* Wild. (1.6 poise; Santoso *et al*., 2012), TRF from johar (*Cassia siamea* Lamk.), sawdust (2.46 and 3.17 poise; Hernawati and Sutoyo, 2018), and TRF from mimosa (6 poise; Zhou and Pizzi, 2013). Tannin extracts are more viscous than synthetic adhesives due to the presence of non-tannin materials and the existence of high molecular weight hydrocolloid gums and tannins (Pizzi, 2003).

However, the viscosity in this study was found to be much lower compared to the PRF in the earlier study (Zhou *et al*., 2017) which recorded 75 poise or 7500 8mpa-s. The proportion of high molecular weight in the tannin extracts is correlated with the high viscosity of tannin solutions (Pizzi, 2018). The high viscosity was intended to reduce the superfluous penetration in wood with high moisture content (Zhou *et al*., 2017). In addition, the high viscous adhesive has a better penetration ability compared to the low viscous adhesive. Bond penetration and durability are infleunced by viscosity (Kamke and Lee, 2007). Moreover, as it slowly flows on the glued material surface, the high viscous adhesive was found to more evenly distribute than low viscous adhesive (Karliati *et al*., 2014).

The pH value of the TRF resin was found to be higher (pH value 10) than the pH value of the PRF standard (pH value 8; Akzonobel, 2017), TRF mangium (pH value 4.0; Rachmawati *et al*., 2018) and phenol formaldehyde with 10%, 20%, and 30% tannin (pH values 8.5; 8.36; 5.97), respectively (Jahanshaei *et al*., 2012). It was however, slightly lower compared to the TRF (pH value 10.5) extracted from *Acacia mangium* Wild. bark (Santoso *et al*., 2012). The polymerization process in adhesive in alkaline pH was halted until all of the reactions were complete. This condition restrained solidification and preserved the adhesive in liquid form. Adhesives with an alkaline pH, therefore, have a longer pot life and prolonged lifetime than the adhesive with acidic pH (Santoso, 2001). A recent study revealed that the high pH value of TRF could be stored longer (± 24 hours) in contrast to the lower pH value of TRF (± 19 hours) before being cured (Auliarta *et al*., 2021). Additionally, adhesives with an acidic pH have a strong effect on holocellulose, while an adhesive with alkaline pH commonly affects lignin (Haygreen and Bowyer, 1993). The acid pH adhesive could be worse for wood strength than a high pH adhesive (Zhang *et al*., 2010).

The TRF in this present study had a specific gravity of 1.07, relatively similar to that reported by Santoso *et al*. (2012). Nevertheless, the value was smaller in comparison to the TRF of *Intsia* spp. (1.14; Santoso *et al*., 2015), the standard PRF (1.15) and TRF of *Acacia mangium* Wild. (1.17; Rachmawati *et al*., 2018). The lower specific gravity value of TRF in this study indicated that its polymer molecular weight was also lower than the TRF of *Instia* spp. (Santoso and Pari, 2015), the standard PRF, and the TRF of *Acacia mangium* Wild (Rachmawati *et al*., 2018). The tannin extracts from mangium bark using basic reagents of different concentrations were approximately 14.67% to 27.81% (Bharudin *et al*., 2013) and 17.7% to 25.8% (Mohamada *et al*., 2010), while Hendrik *et al*. (2019) reported values of 12.59% of tannin mangium bark. It may be noted that the content of mangium tannin was relatively low and results in a low degree of mangium tannin-specific gravity.

Solid content is an vital factor that influences the adhesive during the hot pressing process. The solid content of PRF adhesive in this study was determined to be 23.59%, which was lower than the PRF system 1711 adhesive (57.03%), mangium tannin (46%), johar wood sawdust TRF adhesive (45.73%) formulated in previous studies (Akzonobel, 2017; Hernawati and Sutoyo, 2018; Santoso *et al*., 2012), and magnesium (24.02%; Hendrik *et al*., 2019). A less solid content was, however, obtained in the TRF of merbau wood extracts (19.5%), TRF of *Acacia mangium* Wild (8.33%), and mahogany tannin adhesive (17.65%; Lestari *et al*., 2019; Rachmawati *et al*., 2018; Santoso *et al*., 2015). The low value of the tannin content contributed to the low value of the solid content of the TRF adhesive, among other things. Another factor was probably due to the existence of non-tannin components in the extract (Pizzi, 2003). The non-tannin components reduce the effectiveness of polymerization, thereby potentially impairing resin properties (Pizzi, 2003).

In another similar study, the solid content of TRF was also observed to be affected by the amount of resorcinol and extender added to the formula, where an increase was observed (Abdurachman *et al*., 2021). However, the excessive solid content (37.58%) resulted in a short pot life, hampering adhesive application (Abdurachman *et al*., 2021). Similarly, it was observed in another study that the content of solid resin significantly affected the properties of bonded wood products (Lorenz *et al*., 2007). A high solid content was found to be unfavourable to gluing, while a low solid content resulted in poor bonding (Hoong *et al*., 2012).

Dilution increases the MC of the particles after the application of adhesive. Tannin requires a high MC to ensure proper flow during pressing. The active adhesive content decreases if the amount of extract added remains constant (Dunky, 2021).

Based on the emission test, it was observed that the free formaldehyde of TRF in this study (0.0044%) was ten times lower than the free formaldehyde of standard PRF (0.04%) and TRF of *Acacia mangium* in the previous study (0.09%; Rachmawati *et al*., 2018). The formaldehyde emission from CLTs glued with TRF was determined to be approximately 0.009 mg/L to 0.015 mg/L (Table 3), classed as F**** according to the JAS 234, satisfying the lowest level of formaldehyde emission (JAS, 2003). Similarly, the formaldehyde emissions from tropical hardwoods glulam glued with mangium TRF was reported to be between 0.04 mg/L to 0.05 mg/L, also considered as the F**** type (Hendrik *et al*., 2019). Another study demonstrated that the addition of 10%, 20%, and 30% of condensed *Quercus castaneifolia* C.A. Mey tannin decreased the formaldehyde emission to 1.13, 1.12, and 0.4 mg/100 g, respectively (Jahanshaei *et al*., 2012). This indicates that tannin played a vital role as a formaldehyde scavenger in the bonded products due to the phenolic compounds in the tannin bark extracts (Hoong *et al*., 2012).

Table 3. Descriptive statistics for the physical properties of six-layered cross laminated timber

CLT	Moisture content (%)			Density (g/cm^3)		
	Mean	SD	SE	Mean	SD	SE
C	16.725[e]	0.0289	0.0144	0.455[c]	0.01291	0.00645
S	16.142[c]	0.0275	0.0138	0.340[a]	0.01633	0.00816
J	16.297[d]	0.1004	0.0502	0.395[b]	0.01291	0.00645
CS	15.587[a]	0.0988	0.0494	0.350[a]	0.00000	0.00000
CJ	15.873[b]	0.0340	0.0170	0.430[c]	0.00816	0.00408

[a–e] Values followed by the same letter within a columns are not statistically different based on Tukey's range test.
CLT: cross laminated timber, C: coconut, S: sengon, J: jabon, CS: coconut-sengon, CJ: coconut-jabon.

3.2. Physical properties of cross laminated timber (CLT)

The descriptive statistics for the physical properties of six-layered CLTs are demonstrated in Table 3. Moisture content is defined as the amount of water in wood, calculated as a percentage of oven-dry wood weight (Shmulsky and Jones, 2011). The results demonstrated that the control CLT (C CLT) demonstrated the highest moisture content value (16.725%) compared to J CLT (16.30%) and S CLT (16.142%). Nevertheless, the inclusion of sengon and jabon veneers in the CS CLT (15.587%) and CJ CLT (15.873%) decreased the moisture content values, as opposed to the single C CLT. The ANOVA indicated that the layer composition of CLT significantly affected the moisture content (Table 4). Similarly, Hendrik *et al*. (2019) determined significant effects of wood species, type of adhesive, and the interactions of the two factors on the moisture content of glulam. The moisture content of S CLT produced in this study was higher than those reported in earlier studies that recorded moisture content values of 13%, 12.66%, and 15.95% (Apriliana, 2012; Muthmainnah, 2014; Permatasari, 2014). The moisture content value of the latter was recorded for the sengon CLT-45° panel (Permatasari, 2014). These studies had applied isocyanate to adhere to the laminated wood which had higher solid content compared to the mangium TRF used in this study. A low solid content of tannin-based adhesive thereby resulted in an elevated moisture content of composite products (Dunky, 2021). Non-tannin substances usually found in tannin extracts, such as hydrocolloid gums, are hydrophilic, which, therefore, contributed to the high viscosity and low moisture content (Sowunmi *et al*., 1996).

The lowest moisture content in this study was higher than afrika-jabon (13.01%–13.59%) and jabon-afrika CLTs (13.16%–13.84%; Supartini, 2012), and sengon (14.37%), jabon (14.1%), and mangium glulams (8.55%; Hendrik *et al*., 2019). The moisture content of CLT in this study did not satisfy JAS 1152-2007 for glued laminated timber (JAS, 2007). Further research is ongoing to improve the quality and quantity of TRF adhesive particularly in terms of adherance to fast-growing species composite products. This could also be performed by applying ethanol or acetone with less water volume ratio comparable, as suggested in Harborne (1987). In addition to this, densification (50%) with tannin extract (15%) was carried out to improve the moisture content of coconut wood (Harsono, 2015). The moisture content of densified coconut wood was 8.18% while the control wood was 20.48% (Harsono, 2015). The wood structure has been changed and resulting in water reduction. The moisture content influenced the elasticity, shear modulus (Gülzow *et al*., 2011), and adhesion process of composite products (Frese *et al*., 2012). It was revealed that laminated lumber with 12% moisture content demonstrated 50% greater strength compared to laminated lumber

Table 4. ANOVA for the physical properties of six-layered cross laminated timber

Properties	Sum of squares			*df*			Mean square		*F*-value	*p*-value
	Between groups	Within groups	Total	Between groups	Within groups	Total	Between groups	Within groups		
Moisture content	2.971	0.068	3.039	4	15	19	0.743	0.005	164.320	0.000
Density	0.039	0.002	0.41	4	15	19	0.010	0.000	74.025	0.000

ANOVA: analysis of variance.

with a moisture content of 20% moisture (Frese *et al*., 2012). Further, the high concent of water in wood inhibits the adhesion process (Frese *et al*., 2012). Moisture content of 14% was, therefore, suggested as the maximum value of composite materials (Ruhendi *et al*., 2007). To ensure this, the air temperature and relative humidity of the manufacturing facility should be controlled throughout the manufacturing process (Hänsel *et al*., 2022).

Density is described as the mass per unit of volume and is conversely associated with the proportion of void volume (Shmulsky and Jones, 2011). The C CLT demonstrated the highest density (0.455 g/cm^3) followed by CJ (0.430 g/cm^3), J (0.395 g/cm^3), CS (0.350 g/cm^3), and S CLTs (0.340 g/cm^3; Table 3). The density of S CLT in this study was found to be relatively similar to sengon laminated timber produced in the earlier studies, i.e 0.31 g/cm^3 (sengon glulam), 0.33 g/cm^3 (S CLT-45°), and 0.32 g/cm^3 (S CLT-90°; Hendrik *et al*., 2019; Muthmainnah, 2014; Permatasari, 2014). These findings were also similar to the density values of sengon solid wood—0.24 g/cm^3 to 0.49 g/cm^3—with an average of 0.33 g/cm^3 (Martawijaya *et al*., 2005). The application of mechanical force with appropriate moisture and temperature reduced the porosity of the wood structure, as observed in Feng and Chiang (2020). The study revealed that CLT manufactured from densified sengon had higher MOR and MOE values in comparison to the undensified sengon CLT (Feng and Chiang, 2020).

The ANOVA demonstrated that the layer composition of CLTs significantly affected the CLT density (Table 4). Similar findings were revealed in Supartini (2012) that found a significant effect of wood species on the density of mangium (*Acacia mangium* Willd.)-jabon (*Antocephalus cadamba* Miq.) CLT (0.55－0.57 g/cm^3), afrika (*Maesopsis eminii* Engl.)-jabon CLT (0.42－0.44 g/cm^3) and jabon-afrika CLT (0.43－0.45 g/cm^3), and Supartini (2012). These findings coincided with Tsoumis (1991) who determined that the density of the composite product is influenced by the density of their raw material, in turn affecting the physical and mechanical properties of the manufactured products. The combination of wood species in a composite product should also be carefully selected to prevent delamination of the product (Yusoh *et al*., 2021). Additionally, previous studies determined that the density of the composite products is also affected by cold pressure, veneer thickness, and adhesive layer (Muthmainnah, 2014; Santoso, 1995).

3.3. Mechanical properties of cross laminated timber (CLT)

The descriptive statistics for the mechanical properties of six layered CLT are presented in Table 5. It is assumed that the inclusion of sengon and jabon veneers in the CLT improved its bonding strength. The highest shear strength values were recorded for S CLT (56.31 kg/cm^2) and J CLT (51.99 kg/cm^2) for the dry test (Table 5). The ANOVA revealed that the layer composition of CLT significantly affected the shear strength (Table 6). The shear strength of CJ CLT, however, was found to be slightly higher than C CLT. This may due to the satisfying properties of jabon that contributed to the CLT strength. The different moisture content of the wood species contributed to different bonding strengths of CLT (Knorz *et al*., 2017).

The S CLT produced in the earlier study demonstrated a low shear strength of 10.37 to 48.43 kg/cm^2 and 18.95 kg/cm^2 (Apriliana, 2012; Muthmainnah, 2014). While the former study found that the mechanical properties of CLT were affected by the combination of thickness and angle orientation of the lamina, the latter concluded that the performance of CLT was controlled by the adhesion process. The adhesion process, however, was found to be closely related to the mechanical and chemical factors that contribute to the adhesive capacity (Frihart and Hunt, 2010). It is also important to understand the chemical and mechanical responses of the

Table 5. Descriptive statistics for the mechanical properties of six-layered cross laminated timber (unit: kg/cm^2)

CLT	Shear strength (dry test)			Shear strength (wet test)			MOR			MOE		
	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE
C	33.513[a]	0.445	0.2227	6.352[b]	0.379	0.1896	423.23[a]	13.25	6.625	73,179[d]	70,745	1,048.63
S	56.31[b]	3.37	1.6832	9.530[c]	0.364	0.1820	433.06[ab]	5.22	2.610	54,929[b]	809	404.27
J	51.99[b]	4.32	2.1594	14.585[d]	0.898	0.4490	431.17[ab]	13.86	6.931	47,216[a]	1,512	756.03
CS	29.435[a]	1.392	0.6960	4.330[a]	0.656	0.2683	467.28[b]	17.49	8.745	74,549[d]	3,826	1,912.96
CJ	33.968[a]	1.461	0.7305	5.7225[b]	0.1854	0.0927	632.37[c]	35.7	17.837	63,625[c]	1,571	785.50

[a–d] Values followed by the same letter within a columns are not statistically different based on Tukey's range test.
CLT: cross laminated timber, MOR: modulus of rupture, MOE: modulus of elasticity, C: coconut, S: sengon, J: jabon, CS: coconut-sengon, CJ: coconut-jabon.

bondline to the changes in moisture in the wood (Frihart, 2009). TRF is classified as an *in-situ* polymerization adhesive, based on its chemistry and structure-property relationship. *In-situ* polymerized adhesives have a low molecular weight and can lessen cell wall swelling (Frihart, 2009).

The MOR values of CLTs are presented in Table 5. The highest MOR value was recorded for CJ CLT (632.37 kg/cm^2) and the lowest was C CLT (423.23 kg/cm^2). From the statistical analysis, it was determined that there were significant differences between layer compositions on the value of MOR (Table 6). The MOR value of S CLT in this study was found to be higher (433.06 kg/cm^2) compared to the S CLT (183.74 to 324.10 kg/cm^2) produced in the previous study (Apriliana, 2012). This may be due to the absence of the angle orientation of the lamina in the latter study. The effect of lamina thickness and its angle orientation on the MOR value was found to be significant (Apriliana, 2012). The load-bearing capacity was unevenly distributed as a result of the differentiation in thickness of the lamina (Apriliana, 2012). In regard to the MOR value, the CLTs produced in this study satisfied the requirement set forth by JAS 1152-2007 (JAS, 2007).

Choi *et al*. (2018) produced a composite material from existing CLT and plywood and found that the number of plywood layers significantly affected the MOR values. The hybrid CLT with 3-ply plywood demonstrated higher MOR values (67.8 MPa or 691.37 kg/cm^2) compared to the hybrid CLT with 5-ply plywood (43.9 MPa or 447.65 kg/cm^2). Supartini (2012) similarly concluded that wood species and the number of layers significantly affected the MOR values. The CLT composed from mangium (*Acacia mangium* Willd.) demonstrated the superior MOR value (534.25–603.52 kg/cm^2), while the lowest MOR value was recorded for jabon CLT (329.71–411.57 kg/cm^2; Supartini, 2012). The values tended to decline with the bonding of additional CLT layers (Apriliana, 2012). The transverse direction of composites is often weak, which may lead to delamination and early failure (Shang *et al*., 2019). The adhesive failure or the in-plate force of the plywood further contributed to the low MOR value (Choi *et al*., 2018).

Recent research (Galih *et al*., 2020) recorded a notable MOR value of hybrid CLT made of tropical wood species (mangium) with moso bamboo [*Phyllostachys edulis* (Carriere) J. Houzeau]. The 3-ply-CLT produced in a recent research demonstrated a better performance of bending properties (MOR value = 39.41 MPa or 401.87 kg/cm^2) in comparison to Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] CLT (Galih *et*

Table 6. ANOVA for the mechanical properties of six-layered cross laminated timber

Properties	Sum of squares			*df*			Mean square		*F*-value	*p*-value
	Between groups	Within groups	Total	Between groups	Within groups	Total	Between groups	Within groups		
Shear strength (dry test)	2,377.826	102.766	2,480.592	4	15	19	594.457	6.851	86.768	0.000
Shear strength (wet test)	267.595	4.215	271.810	4	15	19	66.899	0.281	238.067	0.000
MOR	124,624.890	5,920.744	130,545.635	4	15	19	31,156.223	394.716	78.933	0.000
MOE	2.205×10^9	73,332,663.876	2.278×10^9	4	15	19	5.512×10^8	4,888,844.258	112.748	0.000

ANOVA: analysis of variance, MOR: modulus of rupture, MOE: modulus of elasticity.

al., 2020). It was argued that the combination of low-density mangium and the strength of bamboo fiber contributed to this distinction (Galih *et al*., 2020). The MOR value was also influenced by the arrangement of different-density laminas (Prabuningrum *et al*., 2020).

The MOE values of the CLTs are listed in Table 5. It may observed that the highest MOE value was recorded for CS CLT (74,549 kg/cm^2), while the lowest was J CLT (47,216 kg/cm^2). The ANOVA revealed a statistically significant influence on the MOE values of the layer composition of CLT (Table 6). Nevertheless, as the minimum standard for the MOE value set by JAS 1152 is 7.5×10^3 N/mm^2. The CLTs manufactured in this study did not satisfy the standard (JAS, 2007), barring CS CLT which almost satisfied the standard.

The MOE values of solid coconut, CJ, and CS CLTs were determined to be higher than other compositions. This might be due to the higher density of coconut compared to sengon and jabon. There is observed a strong relationship between elasticity and density of the panel, as stated in (Bal and Bektaş, 2012; Kurt, 2010).

A previous study produced CLT from jabon and mangium and found that the flatwise and edgewise MOE values were $8.61–10.37 \times 10^4$ kg/cm^2 and $7.68–8.70 \times 10^4$ kg/cm^2, respectively (Supartini, 2012). It was further found that there were significant differences between the varied number of CLT layers and wood species (Supartini, 2012).

S CLT produced in this study demonstrated a MOE value of 54,928.56 kg/cm^2, while the S CLT manufactured with varied thickness and orientation angles of the lamina in the previous study demonstrated an average MOE value of 50,843 kg/cm^2 (Apriliana, 2012). The performance of the elasticity of MOE depends on the bonding process (Apriliana, 2012; Frihart and Hunt, 2010). A broken bonded joint between lamina would generate an ineffective transfer of stress and loads, thus decreasing wood stiffness (Apriliana, 2012; Frihart and Hunt, 2010).

Similar to MOR values, the MOE values of the hybrid CLT with plywood produced by Choi *et al*. (2018) decreased as the number of plywood layers increased. It was reported that the MOE of hybrid CLT with 3-ply plywood was 10.8 GPa (110,129.4 kg/cm^2), while the MOE of hybrid CLT with 5-ply plywood was 8.6 GPa (87,695.6 kg/cm^2; Choi *et al*., 2018). The increased number of plywood in the CLT generated higher in-plate shear force, thus decreasing the panel elasticity (Choi *et al*., 2018). This may be similar to the CLT produced from lumber. Further work is however required to provide evidence of the influence of several lumber layers on the mechanical properties of CLT. The application of a thick veneer could additionally be an option to increase the MOE value of the panel (Choi *et al*., 2018). The application of thick lumber may also increase the MOE value of CLT.

Aside from setting the appropriate dimension of the manufactured material, selecting the desired raw material successfully increased the MOE value of the hybrid CLT. The hybrid CLT made of mangium and moso bamboo demonstrated a remarkable MOE value of 21.83 GPa (222,604.05 kg/cm^2; Galih *et al*., 2020). This was due to the elasticity of the bamboo fiber used in the panel (Galih *et al*., 2020) which provided strength to the bamboo (Chen *et al*., 2020). Large lumen vessels and parenchyma cells in bamboo also served as a buffer, limiting the occurrence and spread of cracks (Chen *et al*., 2020). The type of plywood longitudinal joint had a strong hand in minimizing the transmission of load to the middle layer, thereby avoiding flexural failure of the CLT (Choi *et al*., 2021).

Table 7 demonstrated that the highest and lowest formaldehyde emissions were 0.0155 mg/L and 0.0095 mg/L, for CJ CLT and J CLT, respectively. These values were lower than the formaldehyde emissions found in glued laminated timber in another study (Hendrik *et al*., 2019). The ANOVA demonstrated a highly significant correlation between the layer composition of CLT and the formaldehyde emission of the composites (Table 8). These findings also confirmed that the existence of phenolic compounds in the tannin extract can react with formaldehyde in the wood panel, thereby reducing the emitted formaldehyde (Hoong *et al*., 2012; Jahanshaei *et al*., 2012). It was reported that formaldehyde emissions of jabon, sengon, and mangium glued laminated timbers that adhered with tannin were 0.05 mg/L, 0.04 mg/L, and 0.04 mg/L, respectively (Hendrik *et al*., 2019). In accordance with JAS 1152 (JAS, 2007), all of the CLTs manufactured in this study demonstrated the lowest level of emission and thus classified as F**** with an emission level of less than 0.3 mg/L. This is the highest level of formaldehyde emitted from solid wood (Zhang *et al*., 2018). F**** (F four stars) represents the highest grade of formaldehyde emission levels that are not subjected to the use area limit (JAS, 2007). This means that wood panels with F**** may be used for indoor applications without restriction.

Table 7. Descriptive statistics for formaldehyde emission of six-layered cross laminated timber

CLT	FE (mg/L)		
	Mean	SD	SE
C	0.0140^{ab}	0.00216	0.0011
S	0.01025^{a}	0.001708	0.0008
J	0.0095^{a}	0.001291	0.0006
CS	0.01400^{ab}	0.001826	0.0009
CJ	0.0155^{b}	0.00342	0.0017

^{a,b} Values followed by the same letter within a columns are not statistically different based on Tukey's range test.
CLT: cross laminated timber, FE: formaldehyde emission, C: coconut, S: sengon, J: jabon, CS: coconut-sengon, CJ: coconut-jabon.

Table 8. ANOVA for the formaldehyde emission of six-layered cross laminated timber

Properties	Sum of squares			*df*			Mean square		*F*-value	*p*-value
	Between groups	Within groups	Total	Between groups	Within groups	Total	Between groups	Within groups		
FE	0.000	0.000	0.000	4	15	19	0.000	0.000	5.660	0.006

ANOVA: analysis of variance, FE: formaldehyde emission.

4. CONCLUSIONS

CLTs made from fast growing species that adhered with TRF from *Swietenia mahagoni* (L.) Jacq. bark demonstrated comparable properties to the standard phenol resorcinol formaldehyde, except for solid content. The CLT made from coconut and jabon boards performed the highest MOR (632.37 kg/cm^2), while CLT made from coconut and sengon boards demonstrated the highest MOE (74,548.76 kg/cm^2). The latter, however, did not meet the JAS 1152-2007 requirement. Additionally, the use of tannin extracts resulted in remarkably low formaldehyde emissions. It is worth mentioning that the use of TRF copolymer resin has the potential to promote environmentally wood products. Further research should be dedicated to improving the inferior properties if the CLT will be used for structural material.

CONFLICT of INTEREST

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

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