Research Article

Sutrisno*, Eka Mulya Alamsyah, Ginanjar Gumilar, Takashi Tanaka, Masaaki Yamada

Improved strength properties of LVL glued using PVAc adhesives with physical treatment-based Rubberwood (*Hevea brasiliensis*)

<https://doi.org/10.1515/opag-2020-0072>

received January 3, 2020; accepted September 10, 2020

Abstract: The properties of the laminated veneer lumber (LVL) composed of the boiled veneer of Rubberwood (*Hevea brasiliensis*) using polyvinyl acetate (PVAc) adhesives in various cold-pressing time and various conditioning time with loaded and unloaded were studied. Five-ply LVL was produced by boiling veneer at 100°C for 90 min as pretreatment and cold-pressing time at 12 kgf cm⁻² for 1.5, 6, 18, and 24 h then conditioned at 20°C and 65% relative humidity (RH) with loaded (12 kgf cm⁻²) and unloaded for 7 days as physical treatment. Especially for the delamination test, the specimens were immersed at 70 ± 3°C for 2 h and dried in the oven at 60 ± 3°C for 24 h; then, the specimens were solidified at room temperature (20°C and 65% RH) with loaded (12 kgf cm⁻²) and unloaded for 7, 10, 12, and 14 days. To determine the performance of LVL, the density, moisture content (MC), delamination, modulus of elasticity (MOE), modulus of rupture (MOR), horizontal shear strength, and formaldehyde emission tests were conducted according to the Japanese Agricultural Standard (JAS 2008) for structural LVL. The MOE and MOR values were significantly influenced by the physical treatment, however, neither to horizontal shear strength nor to formaldehyde emission. The best performance of LVL has resulted from unloaded LVL with cold-pressed time for 18 h; the MOE and MOR values were 9,345.05 ± 141.61 N mm⁻² and 80.67 ± 1.77 N mm⁻²,

respectively. The best value of the horizontal shear strength was obtained from the LVL with 18 h cold-pressing time and conditioned with loaded (13.10 ± 1.47 N mm⁻²) and unloaded (12.23 ± 1.36 N mm⁻²). The percentage of delamination values decreased with an increase in the cold-pressing time and conditioning time. The lowest value of delamination (19.06%) was obtained from the LVL with 24 h cold-pressing time and conditioned with loaded for 14 days. Except the delamination test, all other properties fulfilled the JAS.

Keywords: LVL, Rubberwood, PVAc, cold-pressing, boiled veneer

1 Introduction

In Indonesia, the use of small-diameter logs produced from industrial forest estates has been studied since 1998 due to the decrease of large diameter logs from the natural forest as raw materials for composite wood industries (Kliwon and Iskandar 1998). Rubberwood (*Hevea brasiliensis*) produced from community rubber plantation can be used as a raw material for wood-based panel products because, in comparison with some commercial wood species, it has been shown to exhibit equal or better physical and mechanical properties (Boerhendhy et al. 2003). Additionally, in 2018, Indonesia has the largest rubber plantation with the area ±3,671,387 ha or about 30% of the total area in the world (Ministry of Agriculture of Indonesia 2019). Rubber plantation in Indonesia is still dominated by community rubber plantation (smallholders), which cover an area about 3,235,761 ha (88.13%) followed by government estate 189,576 ha (6.70%) and private estate 2,46,050 ha (5.16%) (Ministry of Agriculture of Indonesia 2019). By assuming that the rubber areas were rejuvenated every year about 2% of smallholders and 3% of government estate and private estate, respectively, and the average wood potential was about 50 m³/year (Boerhendhy et al. 2003), the potential wood

* **Corresponding author: Sutrisno**, School of Life Sciences and Technology, Institut Teknologi Bandung, Jl. Ganesha No. 10 Bandung 40132, West Java, Indonesia, e-mail: sutrisno@sith.itb.ac.id, e-mail: 2015sutrisno@gmail.com; tel: +62-22-251-1575

Eka Mulya Alamsyah: School of Life Sciences and Technology, Institut Teknologi Bandung, Jl. Ganesha No. 10 Bandung 40132, West Java, Indonesia

Ginanjar Gumilar: Alumni of Forestry Faculty, University of Winaya Mukti, Jatinangor Sumedang, Indonesia

Takashi Tanaka, Masaaki Yamada: Faculty of Agriculture, Shizuoka University, Ohya 836, Suruga-ku, Shizuoka, 422-8529, Japan

produced from un-productive of rubber areas reached about 3.9 million m³ every year. The production of LVL from rubberwood using a hot-setting adhesive, especially phenol-formaldehyde (PF), melamine urea-formaldehyde (MUF), and urea-formaldehyde (UF), has been reported (Ding *et al.* 1996; Khoo *et al.* 2019). However, research to improve the properties of LVL manufactured from rubberwood using a cold-setting adhesive, namely PVAc, with physical treatment is very limited.

To improve the adhesion between the wood and adhesive, many pretreatments were applied to wood surfaces such as chemical pretreatments (Gardner and Elder 1988; Belfas *et al.* 1993), mechanical pretreatments using sanding and planning (Aydin 2004a; Folrich *et al.* 2010) or densification by rolling (Bekhta *et al.* 2009) or prepressing (Bekhta 2003; Bekhta and Marutzky 2007), and thermo-mechanical pretreatments using a hydraulic press with electric resistance heating (Arruda and Del Menezzi 2016). Additionally, bonding quality and strength properties of LVL or plywood could be improved by using adhesive filled with the filler (Sutrisno *et al.* 2018; Sutrisno *et al.* 2020) or nanoclay (Moya *et al.* 2015). However, the influence of using hot water at 100°C on veneers as a pretreatment method is yet to be reported. Although boiled logs can be applied to modify the surface characteristics of veneers, to the best of our authors' knowledge, this method is unsuitable for woods that were produced from community forest or industrial plantation forest because the value of wood density is around low (0.24–0.56 g cm⁻³) and medium (0.56–0.72 g cm⁻³) classes (Abdurachman and Hadjib 2009). In addition, thermal treatment on wood at high temperature in the range of 180–250°C could retard and even impair penetration of glues because of the decrease in wettability and surface inactivation by oxidation of wood bonding sites (Costa *et al.* 2014), which is due to the compounds formed in the chemical transformations above 180°C (Esteves and Pereira 2009).

UF resins are the most widely used adhesives in the manufacture of wood-based panels, especially for interior use. However, environmental requirements, such as stringent formaldehyde emission regulations (Carvalho *et al.* 2012), have forced producers to use an alternative adhesive, and one of them is polyvinyl acetate (PVAc) adhesive. PVAc adhesives are widely used and chosen (Král *et al.* 2015) because they are ready-to-use, short setting time, flexible joint, easy to clean, long storage life (Costa *et al.* 2014), odorless, and nonflammable (Uysal 2005). The growing interest in the use of PVAc adhesives in the wood-based industry is due to the health hazards associated with formaldehyde-based adhesives (Kim and Kim 2006), which are inexpensive when compared with

formaldehyde-based adhesives (Paris 2000), various materials can be bonded, and nontoxic (Kim *et al.* 2007).

The use of PVAc in making LVL has been studied by Aydin *et al.* (2004b), Shukla and Kamdem (2008), and Hashim *et al.* (2011). Currently, PVAc adhesives also can be applied to the structural design of wood furniture and wooden constructions (Hu and Guan 2019). Some researches have been conducted to evaluate the bonding performance of PVAc adhesives without any treatment on the wood surface. Kral *et al.* (2015) reported that the bonding properties were affected by different hydrothermal exposures, and the shear strength was affected by the wood species. Additionally, Uysal (2005) reported that the bonding strength of PVAc adhesives was lower than that of UF in the application for LVL after the steam test.

There are several treatments for improving the adhesive strength of PVAc, including the addition of PVAc to silica (SiO₂) and titanium dioxide (TiO₂) nanoparticles (Petkovic *et al.* 2019) and thermal treatment to the wood at 180°C and 200°C for 3, 5, and 7 h (Andromachi and Ekaterini 2018). The bonding strength of PVAc adhesives on the fir wood is decreased in line with the temperature, and the duration of the treatment is increased. On the other hand, Ordu *et al.* (2013) reported that the thermal treatment on pinewood at 100–150°C for 4 h increased the performance of PVAc adhesives by 31.51%. All these treatments had led to an increase in the price of PVAc adhesives.

However, to the best of our authors' knowledge, the use of physical treatments such as boiling veneers, various cold-pressing time and conditioning time, and type of the conditioning method (with loaded and unloaded) on the bonding properties of PVAc adhesives has not been reported. The purpose of this research was to improve the performance of PVAc adhesives by using the above-mentioned physical treatments on the production of LVL made from rubberwood, especially for interior use. The physical and mechanical properties of LVL were evaluated, including density, moisture content (MC), delamination, modulus of elasticity (MOE), modulus of rupture (MOR), horizontal shear strength, and formaldehyde emission.

2 Materials and methods

2.1 Materials

The wood species used was rubberwood (*Hevea brasiliensis*) from the Community Rubber Plantation at South Sumatera Province, Indonesia. Rubberwood used in this

Table 1: Specification of PVAc

Specification	Justification
Color	White
Viscosity	10,000–15,000 mPa s
Solid content	$36 \pm 1.01\%$
pH	4–6
Boiling point	100°C
Freezing point	0°C
Specific gravity	1.1–1.2

experiment was harvested after cessation of latex with the age of tree 26 years and the solid wood density is 0.67 g cm^{-3} . PVAc emulsion was used in this study. The PVAc specification used in this study is listed in Table 1.

2.2 Methods

2.2.1 Preliminary study

The preliminary study aims to study the effects of pretreatment of veneer and to select better pretreatment by boiling the veneer at a temperature of 100°C for 2, 4, 6, 8, 10, 15, 30, 45, 60, 75, and 90 min or soaking the veneer in acetic acid at a concentration of 10% for 2, 4, 6, 8, 10, 15, 30, 45, 60, 75, and 90 min. Three specimens of LVL were produced using two various pretreatments of veneer, cold-pressing at 12 kgf cm^{-2} for 24 h and conditioned at 20°C and 65% RH for 3, 5, and 7 days before evaluating their delamination values according to the Japanese Standard (Japanese Agricultural Standard 2008) for structural laminated veneer lumber. Based on this standard, the percentage of delamination values are categorized as follows: passed (<10%), retest (10–30%), and failed (>30%).

2.2.2 Differential scanning calorimetry (DSC) analysis

The thermal properties of PVAc adhesives were studied by DSC analysis following the procedure by Jelinska et al. (2010) and Cowan et al. (1978). The samples were prepared by casting wet films of emulsion on Teflon container, dried at room temperature for 24 h, and then dried at 60°C for 24 h in a vacuum oven. Approximately 2 mg of the sample was heated at a heating rate of 10°C/min from –30 to 150°C in a nitrogen atmosphere. Thermal transitions were measured using a differential scanning calorimeter (DSC-60 Calorimeter, Shimadzu).

2.2.3 LVL manufacturing

Five-ply LVL was made from rubberwood veneer with 1.7 mm thick, 35 cm length, and 35 cm width boiled at 100°C for 90 min as pretreatment and dried until MC of veneer reached about 8%. Then, the glue was applied on both sides of core veneer at a spread rate of 32 g f^{-2} followed immediately by covering face and back veneer and cold-pressing at 12 kgf cm^{-2} for 1.5, 6, 18, and 24 h. The LVLs were thereafter conditioned at room temperature (20°C and 65% relative humidity (RH)) for 7 days with loaded (12 kgf cm^{-2}) and unloaded before testing. For the delamination test, the specimens were immersed at $70 \pm 3^\circ\text{C}$ for 2 h and dried at $60 \pm 3^\circ\text{C}$ for 24 h, then solidified for 7, 10, 12, and 14 days at room temperature (20°C and 65% RH) with loaded (12 kgf cm^{-2}) and unloaded before testing. The specimens were cold-pressed at a pressure of 12 kgf cm^{-2} , which is used as the conditioning method with loaded.

2.2.4 Density and moisture content (MC) test

Four pieces of $50 \times 50 \text{ mm}$ specimens were used to determine the density and MC using the gravimetric method. In the density test, specimens were taken from air-dried weight panel, and then the air-dried volume was measured and calculated using equation (1):

$$\text{Density (g cm}^{-3}\text{)} = \frac{\text{Air-dried weight}}{\text{Air-dried volume}}. \quad (1)$$

MC was calculated using equation (2):

$$\text{MC (\%)} = \frac{\text{Weight before drying} - \text{Oven-dried weight}}{\text{Oven-dried weight}}. \quad (2)$$

2.2.5 Modulus of elasticity (MOE) and modulus of rupture (MOR) test

MOE and MOR were evaluated according to JAS (Japanese Agricultural Standard 2008) for Structural Laminated Veneer Lumber. Two types of specimens for MOE and MOR tests, flat-sample and edge-sample, were used, and the sample configurations are shown in Figure 1. The load was applied perpendicular and parallel to the veneer faces for flatwise and edgewise bending, respectively. The size of the flat-sample is as follows: length ($23 \times \text{LVL thickness}$) and width (90 mm); and the size of the edge-sample is as follows: long ($23 \times \text{LVL thickness}$) and width (LVL thickness). LVL thickness is the dimension of

Figure 1: LVL sample configurations: flat (a) and edge (b).

a cross section, which is perpendicular to the plane of the veneers, and measured in the Y-direction, while LVL width is the dimension of a cross-section, which is perpendicular to the thickness (or parallel to the plane of the veneers) and measured in the X-direction (Figure 1). Four specimens from each panel were used. MOE and MOR were calculated using equations (3) and (4), respectively:

$$\text{MOR (N mm}^{-2}\text{)} = \frac{\Delta PL^3}{4\Delta ybh^3}, \quad (3)$$

$$\text{MOR (N mm}^{-2}\text{)} = \frac{3PL}{2bh^2}, \quad (4)$$

where P is the maximum load (N), b is the width of test specimens (mm), L is the span (mm), h is the thickness of test specimens (mm), ΔP is the difference between upper and lower limits of load within proportional range (N), and Δy is the deflection at the center of span corresponding to ΔP (mm).

2.2.6 Horizontal shear strength test

Horizontal shear strength was evaluated according to JAS (Japanese Agricultural Standard 2008) for Structural Laminated Veneer Lumber. Two types of specimens for the horizontal shear strength test, flat-sample and edge-sample, were used, and the sample configurations are shown in Figure 1. The size of flat-sample is as follows: long ($6 \times \text{LVL thickness}$) and width (40 mm), and the size of edge-sample is as follows: long ($6 \times \text{LVL thickness}$) and width (LVL thickness). Four specimens from sample configurations (flat and edge) were used, and then the adhesive strength test is applied to the test specimens

under the dry condition to obtain the horizontal shear strength. The bonding strength was calculated using equation (5):

$$\begin{aligned} \text{Horizontal shear strength (N mm}^{-2}\text{)} \\ = \frac{\text{Maximum load at failure}}{\text{Glued area}}. \end{aligned} \quad (5)$$

2.2.7 Percentage of delamination test

The percentage of delamination was evaluated according to JAS (Japanese Agricultural Standard 2008) for Structural Laminated Veneer Lumber. Four specimens from each panel with a size of 75×75 mm were used for the delamination test. Specimens were immersed into hot water at $70 \pm 3^\circ\text{C}$ for 2 h then dried at $60 \pm 3^\circ\text{C}$ for 24 h, until MC reached below or equal to 8%. After that, samples were solidified for 7, 10, 12, and 14 days at room temperature (20°C and 65% RH) with loaded (12 kgf cm^{-2}) and unloaded before tested. The percentage of delamination was calculated using equation (6):

$$\begin{aligned} \text{Percentage of delamination (\%)} \\ = \frac{\text{Total length of delamination at the 4 side}}{\text{Total length of glue layer at the 4 side}} \\ \times 100\%. \end{aligned} \quad (6)$$

2.2.8 Formaldehyde emission test

Formaldehyde emission was evaluated according to JAS (Japanese Agricultural Standard 2008) for Structural

Laminated Veneer Lumber. Four pieces of the LVL sample of 15 × 5 cm were cut from each panel and wrapped in a plastic bag and then conditioned at room temperature (20 ± 1°C) for more than 1 day. The samples were arranged on the top of a crystallizing dish with 300 mL of distilled water and placed in a glass desiccator. Then, they were conditioned at room temperature (20 ± 1°C) and 65% RH for 24 h. Later, 25 mL liquid sample of distilled water was placed in to Erlenmeyer glass and added 25 mL of acetylacetone ammonium acetate and warmed in a water-bath at 60 ± 2°C for 10 min then conditioned until reached the room temperature in the darkroom. To detect formaldehyde emission, the absorbance of samples is measured based on the 412 nm wave-length using spectrophotometry. The concentration of emission is calculated based on the standard curve for LVL.

2.3 Statistical analysis

The results of MOE, MOR, horizontal shear strength, and formaldehyde emission were first subjected to an analysis of variance (ANOVA) at $p < 0.05$, and significant differences between mean values were determined using least significance different (LSD) test.

3 Results

3.1 Preliminary study

LVL delamination test results from the preliminary study are listed in Tables 2–4. A preliminary study presented

that a delamination test of LVL produced from boiled veneer at the temperature of 100°C for 90 min, cold-pressed at 12 kgf cm⁻² for 24 h, and conditioned at 20°C and 65% RH for 7 days before testing has the best result with the percentage of delamination 9% (Table 3). This delamination test has passed according to JAS (Japanese Agricultural Standard 2008) (less than 10%); conversely, the percentage of delamination of LVL without pretreatment (control) is higher (45%) as listed in Table 4. This value indicated that due to an increase in the boiling time of the veneer and the conditioned time of LVL before tested, the bonding strength of PVAc adhesives increased significantly. For a temperature of 100°C as boiled veneer pre-treatment, the best performance of delamination is attained after 90 min and conditioned of LVL (20°C and 65% RH) after 7 days. This research successfully assessed that the bonding properties of LVL are significantly altered by different soaked veneer pre-treatment, the period time of boiled veneer, and conditioned of LVL. These results of the preliminary study were expected that will lead to new gluing approaches, which will result in significant performance improvements of veneer-based products.

3.2 Differential scanning calorimetry (DSC) analysis

The DSC analysis was conducted on the PVAc adhesive to determine its glass transition temperature. The glass transition temperature (T_g) is the temperature at which the transition between the glassy and rubbery state of amorphous solids occurs and it is a direct measurement of molecular mobility and depends on its degree of cure (Carbas 2014).

Based on the DSC data, in the first heating cycle shows a glass transition in the temperature range 38.29–42.88°C,

Table 2: Percentage of delamination of LVL

Pre-treatment of veneer	Duration of pre-treatment (min)														
	2			4			6			8			10		
	Conditioning (day)														
	3	5	7	3	5	7	3	5	7	3	5	7	3	5	7
Boiled in water	88 ±	85 ±	83 ±	86 ±	55 ±	52 ±	89 ±	82 ±	72 ±	85 ±	52 ±	53 ±	83 ±	69 ±	63 ±
at 100°C	1.82	3.91	1.41	1.63	2.94	3.83	1.63	2.16	2.94	3.91	2.94	2.94	3.74	2.16	1.41
Soaked in	93 ±	41 ±	31 ±	90 ±	65 ±	46 ±	87 ±	67 ±	50 ±	86 ±	40 ±	19 ±	77 ±	83 ±	64 ±
acetic acid	2.94	1.63	1.15	2.71	2.16	2.94	2.16	1.15	2.16	1.41	1.82	1.63	2.94	2.94	2.94

Figure 2: Thermogram of PVAc in the temperature range 38.29–42.88°C, with flexion at 39.14°C (a), and 39.37–43.68°C with flexion at 40.96°C (b).

Table 5: Average value of density

Cold-pressing time (h)	Density ^a (g cm ⁻³) ± S.d.	
	Unloaded	Loaded
Control	0.67 ± 0.07	0.68 ± 0.08
1.5	0.68 ± 0.08	0.69 ± 0.07
6	0.67 ± 0.08	0.69 ± 0.07
18	0.67 ± 0.07	0.71 ± 0.08
24	0.68 ± 0.07	0.71 ± 0.06

^a Average of four replications; S.d.: standard deviation.

Table 6: Average value of moisture content

Cold-pressing time (h)	Moisture content ^a (%) ± S.d.	
	Unloaded	Loaded
Control	10.93 ± 0.82	11.21 ± 0.82
1.5	8.12 ± 0.80	9.98 ± 0.82
6	9.72 ± 0.81	10.70 ± 0.78
18	10.24 ± 0.83	10.36 ± 0.81
24	10.09 ± 0.81	11.03 ± 0.81

^a Average of four replications; S.d.: standard deviation.

Table 7: Average value of modulus of elasticity of unloaded LVL

Cold-pressing time (h)	Modulus of elasticity ^a (N mm ⁻²) ± S.d.				
	Unloaded flat-sample	Unloaded edge-sample	Average values of unloaded flat and edge-sample	JAS grade	Comparison with control (%)
Control	7100.94 ± 94.59	8514.92 ± 20.72	7807.93 ^d ± 44.53	70 E	—
1.5	8835.20 ± 167.35	7,280.29 ± 113.76	8057.75 ^c ± 102.61	80 E	+3.20
6	8273.63 ± 142.15	9252.57 ± 41.71	8763.10 ^b ± 91.93	80 E	+12.23
18	8934.19 ± 112.19	9755.90 ± 200.15	9345.05 ^a ± 141.61	90 E	+19.69
24	6332.22 ± 78.05	9774.48 ± 200.03	8053.35 ^c ± 137.96	80 E	+3.14

^a Average of four replications; S.d.: standard deviation; values followed by similar letters under the same column are not significantly different at $p = 0.05$ according to LSD test.

3.5 Modulus of rupture (MOR)

The average values of MOR for both conditions, unloaded and loaded LVL, in control and various cold-pressing time from 1.5 up to 24 h are given in Tables 9 and 10. The data showed that the MOR of the LVLs produced using cold-pressing time from 1.5 up to 24 h was significantly increased, ranging from 19.52 to 29.15% (unloaded) and 4.38 to 20.89% (loaded) when compared with the control. However, the MOR of unloaded LVL with cold-pressed time 24 h was decreased by 1.51% when compared with the control. The highest MOR value of $92.32 \pm 2.96 \text{ N mm}^{-2}$ was obtained from loaded LVL with cold-pressed for 18 h (Table 10), and this value increased 40.92% when compared with the control. These MOR values met the 80 E – Special grade requirement based on the Japanese Agricultural Standard (2008), which are listed in Table 11.

3.6 Horizontal shear strength

The average values of horizontal shear strength that represents bonding strength, for both conditions, unloaded

Table 8: Average value of modulus of elasticity of loaded LVL

Cold-pressing time (h)	Modulus of elasticity* (N mm^{-2}) $\pm$ S.d.				
	Loaded flat-sample	Loaded edge-sample	Average values of loaded flat and edge-sample	JAS grade	Comparison with control (%)
Control	6372.30 $\pm$ 92.24	8255.97 $\pm$ 39.99	7314.14 ^d $\pm$ 45.53	70 E	—
1.5	7570.25 $\pm$ 135.48	7698.70 $\pm$ 126.84	7634.48 ^c $\pm$ 91.09	70 E	+4.38
6	6879.90 $\pm$ 185.18	10461.80 $\pm$ 58.58	8670.85 ^b $\pm$ 21.88	80 E	+18.55
18	7955.70 $\pm$ 104.59	9728.54 $\pm$ 224.60	8842.12 ^a $\pm$ 164.60	80 E	+20.89
24	7783.60 $\pm$ 83.04	9822.65 $\pm$ 204.43	8803.13 ^{a,b} $\pm$ 101.99	80 E	+20.36

*Average of four replications; S.d.: standard deviation; values followed by similar letters under the same column are not significantly different at $p = 0.05$ according to LSD test.

and loaded LVL in control, and various cold-pressing time from 1.5 up to 24 h are listed in Tables 12 and 13. Although the horizontal shear strength of the LVLs did not increase significantly by increasing the cold-pressing time from 1.5 to 24 h, the values improved when compared with the control by 20.68 and 18.67% from unloaded and loaded LVL with cold-pressed for 18 h, respectively. All of the values of horizontal shear strength met the 65 V – 55 H grade requirement based on the Japanese Agricultural Standard (2008) as listed in Table 14.

3.7 Percentage of delamination

The values of percentage of delamination for both conditions, unloaded and loaded LVL in control, and various cold-pressing time from 1.5 up to 24 h are listed in Tables 15 and 16. These values had not met the Japanese Agricultural Standard (2008) requirement because the values were more than 10%. These values indicated that the percentage of delamination decreased by increasing the cold-pressing time and solidification time both with loaded and unloaded, whereas with the loaded treatment of LVL showed better performance (19.06%) than that of the unloaded LVL (20.63%).

3.8 Formaldehyde emission

Average values of formaldehyde emission for both conditions, unloaded and loaded LVL in control, and various cold-pressing time from 1.5 to 24 h were around 0.1 mg L^{-1} , which are listed in Table 17, and formaldehyde emission met F4S (or F****) classification of the Japanese Agricultural Standard (2008), showing the emission values lower than 0.3 mg L^{-1} (Table 18). It means that all of the LVLs

resulted in this research had the best value of formaldehyde emission.

4 Discussion

In general, LVL produced from boiled veneer at the temperature of 100°C for 90 min as pretreatment then conditioned (20°C and 65% RH) for 7 days provides performance, meeting the physical and mechanical properties according to JAS (Japanese Agricultural Standard 2008), except the delamination test. It was predicted that the surface of the boiled veneer is already clean from the extractives, which improved the contact between the adhesive and the veneer. As stated by Vick (1999), the condition of the wood surface is extremely important to satisfactory joint performance; hence, the surface should be free of burnishes, exudates, oils, dirt, and other debris. Over-drying and overheating deteriorate the physical condition of the wood surfaces by forcing extractives to diffuse to the surface, by reorienting surface molecules, and by irreversibly closing the larger micropores of cell walls. Wood surfaces can be chemically inactivated with respect to adhesion by airborne chemical contaminants, hydrophobic, and chemically active extractives from the wood. Similar to this research results, Rohumaa (2016) reported that the effect of heating logs before peeling is improved by the bonding strength of plywood due to minimizing the initiation of glue line failure. Furthermore, the higher temperatures of soaking and peeling due to the lower lathe check depth improve the integrity and surface physicochemical properties, such as wettability and roughness (Rohumaa 2016).

The duration of cold-pressing time from 1.5 to 24 h has significantly increased the value of MOE, both in the unloaded and loaded LVL, respectively (Tables 7 and 8).

Table 9: Average value of modulus of rupture of unloaded LVL

Cold-pressing time (h)	Modulus of rupture* (N mm ⁻²) ± S.d.				
	Unloaded flat-sample	Unloaded edge-sample	Average values of unloaded flat and edge-sample	JAS grade	Comparison with control (%)
Control	57.08 ± 2.45	77.90 ± 1.61	67.49 ^c ± 1.07	70 E – Special grade	—
1.5	91.79 ± 6.18	72.01 ± 1.40	81.90 ^b ± 3.76	80 E – Special grade	+21.35
6	91.50 ± 3.50	82.82 ± 1.37	87.16 ^a ± 2.44	80 E – Special grade	+29.15
18	84.72 ± 2.73	76.61 ± 2.49	80.67 ^b ± 1.77	90 E – Special grade	+19.52
24	56.34 ± 2.19	76.61 ± 2.49	66.47 ^c ± 2.14	80 E – Special grade	–1.51

*Average of four replications; S.d.: standard deviation; values followed by similar letters under the same column are not significantly different at $p = 0.05$ according to LSD test.

Table 10: Average value of modulus of rupture of loaded LVL

Cold-pressing time (h)	Modulus of rupture* (N mm ⁻²) ± S.d.				
	Loaded flat-sample	Loaded edge-sample	Average values of loaded flat and edge-sample	JAS grade	Comparison with control (%)
Control	50.50 ± 2.02	80.52 ± 1.64	65.51 ^c ± 0.40	70 E – Special grade	—
1.5	87.30 ± 2.86	79.94 ± 2.84	83.62 ^b ± 2.85	70 E – Special grade	+27.64
6	62.20 ± 2.05	99.40 ± 1.09	80.80 ^b ± 1.57	80 E – Special grade	+23.34
18	90.50 ± 2.69	94.13 ± 3.22	92.32 ^a ± 2.96	80 E – Special grade	+40.92
24	89.05 ± 3.71	95.11 ± 1.96	92.08 ^a ± 2.84	80 E – Special grade	+40.56

*Average of four replications; S.d.: standard deviation; values followed by similar letters under the same column are not significantly different at $p = 0.05$ according to LSD test.

Table 11: Classification of Young's modulus of bending (JAS 2008)

Classification of Young's modulus of bending	Young's modulus of bending or MOE (N/mm ²)		Bending strength or MOR (N/mm ²)		
	Average ($\times 10^3$)	Minimum ($\times 10^3$)	Special grade	Grade 1	Grade 2
180 E	18.0	15.5	67.5	58.0	48.5
160 E	16.0	14.0	60.0	51.5	43.0
140 E	14.0	12.0	52.5	45.0	37.5
120 E	12.0	10.5	45.0	38.5	32.0
110 E	11.0	9.0	41.0	35.0	29.5
100 E	10.0	8.5	37.5	32.0	27.0
90 E	9.0	7.5	33.5	29.0	24.0
80 E	8.0	7.0	30.0	25.5	21.5
70 E	7.0	6.0	26.0	22.5	18.5
60 E	6.0	5.0	22.5	19.0	16.0

Table 12: Average value of horizontal shear strength of unloaded LVL

Cold-pressing time (h)	Horizontal shear strength* (N mm ⁻²) $\pm$ S.d.				
	Unloaded flat-sample	Unloaded edge-sample	Average values of unloaded flat and edge-sample	JAS grade	Comparison with control (%)
Control	8.34 $\pm$ 1.81	11.92 $\pm$ 1.14	10.13 ^a $\pm$ 1.46	65 V – 55 H	—
1.5	11.33 $\pm$ 1.85	12.53 $\pm$ 1.78	11.93 ^a $\pm$ 0.87	65 V – 55 H	+17.77
6	11.26 $\pm$ 1.69	11.45 $\pm$ 1.71	11.36 ^a $\pm$ 1.53	65 V – 55 H	+12.09
18	12.48 $\pm$ 1.73	11.97 $\pm$ 1.45	12.23 ^a $\pm$ 1.36	65 V – 55 H	+20.68
24	9.11 $\pm$ 1.53	12.16 $\pm$ 1.60	10.64 ^a $\pm$ 1.57	65 V – 55 H	+4.99

*Average of four replications; S.d.: standard deviation; values followed by similar letters under the same column are not significantly different at $p = 0.05$ according to LSD test.

Table 13: Average value of horizontal shear strength of loaded LVL

Cold-pressing time (h)	Horizontal shear strength* (N mm ⁻²) $\pm$ S.d.				
	Loaded flat-sample	Loaded edge-sample	Average values of loaded flat and edge-sample	JAS grade	Comparison with control (%)
Control	10.42 $\pm$ 1.62	11.65 $\pm$ 1.41	11.04 ^a $\pm$ 0.40	65 V – 55 H	—
1.5	11.07 $\pm$ 1.78	12.19 $\pm$ 1.71	11.63 ^a $\pm$ 1.55	65 V – 55 H	+5.39
6	11.11 $\pm$ 1.55	14.02 $\pm$ 1.63	12.62 ^a $\pm$ 0.71	65 V – 55 H	+14.36
18	12.22 $\pm$ 1.84	13.97 $\pm$ 1.90	13.10 ^a $\pm$ 1.47	65 V – 55 H	+18.67
24	9.75 $\pm$ 1.60	12.91 $\pm$ 1.54	11.33 ^a $\pm$ 1.34	65 V – 55 H	+2.67

*Average of four replications; S.d.: standard deviation; values followed by similar letters under the same column are not significantly different at $p = 0.05$ according to LSD test.

However, the MOE of the unloaded flat sample with cold-pressed time for 24 h was lower than that of the control. The cold-pressing time for 18 h has resulted in the highest, improving the MOE by up to 19.69% (unloaded) and 20.89% (loaded). The MOE of loaded LVL with cold-pressed time for 18 h met the 80 E grade requirement,

while unloaded LVL upgraded the LVL to 90 E grade requirement according to JAS (2008) as given in Table 11.

The value of MOR, both in the unloaded and loaded LVL, was significantly influenced by cold-pressing time from 1.5 up to 24 h (Tables 9 and 10). However, the MOR of unloaded flat and edge sample with cold-pressed time

Table 14: Horizontal shear strength performance (JAS 2008)

Horizontal shear performance	Horizontal shear strength (N/mm ²)	
	Direction of vertical use (or edgewise strength)	Direction of horizontal use (or flatwise strength)
65 V – 55 H	6.5	5.5
60 V – 51 H	6.0	5.1
55 V – 47 H	5.5	4.7
50 V – 43 H	5.0	4.3
45 V – 38 H	4.5	3.8
40 V – 34 H	4.0	3.4
35 V – 30 H	3.5	3.0

for 24 h was lower than that of the control. The cold-pressing time for 18 h has resulted in the highest, improving the MOR by up to 40.92% in the loaded LVL, while unloaded LVL was 29.15% obtained from cold-pressed time for 6 h. Although the cold-pressing time for 18 h has improved the MOR of the unloaded LVL by up to 19.52%, the MOR of the unloaded edge sample was lower than that of the control. The MOR of the loaded LVL with cold-pressed time for 18 h met the 80 E – Special grade requirements, while the unloaded LVL upgraded the LVL to 90 E – Special grade requirement according

to JAS (2008) as given in Table 11. In line with this result, Ding et al. (1996) reported that LVL produced from rubberwood glued using MUF adhesive had the 80 E – Special grade.

The application of LVL in the building construction or other purposes has not been mentioned in JAS (2008) for Structural Laminated Veneer Lumber. However, based on the strength class and durability class of rubberwood, III–II and V, respectively (Abdurachman and Hadjib 2009), for obtaining the adequate results, the rubberwood LVL is used in building constructions after preserved using a wood preservative material. However, it can be used for interiors only because the rubberwood LVL was produced using PVAc adhesives.

Although the average horizontal shear strength value of LVL was not significantly different, it attributed that the value increased slightly with an increase in the cold-pressing time from 1.5 up to 24 h (Tables 12 and 13). However, the horizontal shear strength of loaded flat samples with cold-pressed time for 24 h was lower than that of the control. Generally, the shear retention of LVL was higher in the cold-pressed time for 1.5 up to 18 h, which recorded 17.77–20.68% and 5.39–18.67% shear retention of unloaded and loaded, respectively, when compared with 4.99 and 2.67% in the cold-pressed time for 24 h. The occurrence of shear retention indicates that there was

Table 15: Average value of percentage of delamination of unloaded LVL

Cold-pressing time (day)	Percentage of delamination* (%) ± S.d.			
	Unloaded sample/duration of conditioning time (day)			
	7	10	12	14
1.5	61.50 ± 1.93	65.42 ± 1.83	46.35 ± 1.83	42.06 ± 1.86
6	84.25 ± 1.82	76.06 ± 1.82	45.56 ± 1.83	42.50 ± 1.72
18	60.50 ± 1.88	61.35 ± 1.82	49.33 ± 1.82	48.33 ± 1.85
24	56.50 ± 1.84	57.19 ± 1.84	53.13 ± 1.83	20.63 ± 1.82

*Average of four replications; S.d.: standard deviation.

Table 16: Average value of percentage of delamination of loaded LVL

Cold-pressing time (day)	Percentage of delamination* (%) ± S.d.			
	Loaded sample/duration of conditioning time (day)			
	7	10	12	14
1.5	56.50 ± 1.79	73.65 ± 1.83	46.35 ± 1.82	37.85 ± 1.82
6	40.25 ± 1.62	72.50 ± 1.48	39.38 ± 1.41	38.38 ± 1.81
18	40.50 ± 1.76	51.67 ± 1.83	34.73 ± 1.80	40.52 ± 1.39
24	25.50 ± 1.94	40.79 ± 1.83	39.38 ± 1.42	19.06 ± 1.64

*Average of four replications; S.d.: standard deviation.

Table 17: Average value of formaldehyde emission

Cold-pressing time (h)	Formaldehyde emission* (mg L^{-1}) $\pm$ S.d.	
	Unloaded sample	Loaded sample
Control	$0.10^a \pm 0.01$	$0.10^a \pm 0.02$
1.5	$0.10^a \pm 0.03$	$0.10^a \pm 0.05$
6	$0.10^a \pm 0.01$	$0.10^a \pm 0.02$
18	$0.10^a \pm 0.01$	$0.10^a \pm 0.02$
24	$0.10^a \pm 0.02$	$0.10^a \pm 0.02$

*Average of four replications; S.d.: standard deviation; values followed by similar letters under the same column are not significantly different at $p = 0.05$ according to LSD test.

Table 18: Classification of formaldehyde emission (JAS 2008)

Class of making	Average value (mg L^{-1})	Maximum value (mg L^{-1})
F****	0.3	0.4
F***	0.5	0.7
F**	1.5	2.1
F*	5.0	7.0

F* is means one star; F** is means two stars; F*** is means three stars; F**** is means four stars (the best performance of formaldehyde emission).

no particular weak zone in the LVL, hence eliminating the possibility of bonding inefficiency at the interface of each layer of veneer.

Based on the Japanese Agricultural Standard (2008) for Structural Laminated Veneer Lumber as shown in Table 14, the horizontal shear strength value met the 65 V – 55 H grade requirement. It means that all of LVL resulted in this research had the first-class performance because it had edgewise and flatwise strength more than 65 and 55 N mm^{-2} , respectively, and used in building constructions in the direction of vertical or horizontal use. In the direction of vertical use, the load was applied parallel to the veneer faces. While in the direction of horizontal use, the load was applied perpendicular to the veneer faces. The LVL obtained in this research is better when compared with the study by Ding et al. (1996) who reported that LVL produced from rubberwood glued using MUF adhesive had the 55 V – 47 H grade.

Conversely, the delamination obtained for the tested LVL did not meet JAS (Japanese Agricultural Standard 2008) requirement with the minimum value of percentage of delamination obtained in this research is 19.06%, which is more than 10%. However, the values of the percentage of delamination are decreasing with an increase in the cold-pressing time and conditioned time of LVL

(Tables 15 and 16). It is clear that at room temperature, PVAc adhesives did not yet cure completely due to the Tg, which approximately reached at 40°C in this research (Figure 2). This is because below the minimum film-forming temperature, the molecule is confined at the site with a very limited group or branch movement freedom, and its free volume is relatively small; hence, whole molecules cannot move away from each other (Li 2000). In addition, there are many factors that affect Tg, such as curing time and curing temperature (Carbas et al. 2014). The process of adhesion is essentially completed after the transition of the adhesive from liquid to solid form. Especially in the thermoplastics adhesive type, the physical change to solid form may occur by either loss of solvent from the adhesive through evaporation and diffusion into the wood or cooling of molten adhesive on a cooler surface (Vick 1999). It was predicted that conditioned time with loaded or unloaded treatment up to 14 days was not sufficient to improve the delamination performance of PVAc adhesives.

On the other hand, rubberwood is one of the resinous species that contain extractives on wood surfaces, which affect the principal physical and chemical contributors to surface inactivation, hence to poor wettability by adhesives (Vick 1999). Komarayati et al. (1995) reported that rubberwood with the age of tree 26 years contained high extractives (more than 4%) due to its resinous species with solubility as follows: in cold water 4.48%, in hot water 5.93%, in alcohol-benzene (1:2) 2.37%, and in 1% sodium hydroxide 20.72%. The acidity of extractives can interfere with the chemical cure of adhesives. Additionally, the low-molecular wood extractives migrate to the surface resulted in natural surface inactivation process then caused the poor adhesion between the wood and adhesive (Back 1998).

The bond ability of wood is not only affected by the surface properties of wood adherents but also affected by wood's physical properties, especially density. Rubberwood used in this research with a density of 0.67 g cm^{-3} is categorized as medium-density wood (Abdurachman and Hadjib 2009). Hence, much greater pressure is required to compress stronger or a longer conditioned time to bring intimate contact between the wood surface and adhesive. This is in agreement with Alamsyah (2008) who studied that the bonding performance of *Enterolobium cyclocarpum*, *Paraserianthes falcataria*, and *Toona sinensis* with the density ranges from 0.30 to 0.49 g cm^{-3} met the requirement of JAS (Japanese Agricultural Standard 2008) in delamination test for both of aqueous polymer isocyanate (API) and resorcinol formaldehyde (RF) adhesives, while with the density ranges from 0.51 to 0.64 g cm^{-3} , *Gmelina arborea* bonded with

API and RF, *Pinus merkusii* and *Acacia mangium* bonded with RF did not meet the requirement of JAS (Japanese Agricultural Standard 2008) in the delamination test. The reason appears to be the great swelling pressure resulting from the high level of wood density acting on the glue layer (Vick 1999). For wood adhesive bonds, the most critical bond stress usually comes not from temperature but from swelling and shrinking of the wood in response to moisture changes, especially full soaking and drying cycles (Vick 1999). This is in line with Konnerth et al. (2016), in general, high-density wood species needed much more time to reach the initial mass demanded during re-drying after the impregnation steps with water than that lower density wood. Furthermore, higher concentrations of extractives that may interfere with the cure of adhesives are common in higher density species than that in a lower density of wood, especially in tropical hardwoods. The severe stresses produced by high-density species as the change dimension with changes in MC also contribute heavily to bonding difficulties (Vick 1999).

Formaldehyde emission of rubberwood LVL glued using PVAc adhesives was not influenced by the cold-pressing time from 1.5 to 24 h and the method of conditioned (unloaded and loaded). The average values of formaldehyde emission obtained in this research were 0.1 mg L^{-1} (Table 17), and it met F4S (or F****) classification according to the Japanese Agricultural Standard (2008), showing the emission values lower than 0.3 mg L^{-1} (Table 18) and could be categorized into the best value of formaldehyde emission. These results were supported by Carvalho et al. (2012), Uysal (2005), Kim and Kim (2006), and Kim et al. (2007) who found that PVAc adhesives are acceptable in use as a wood adhesive due to environmental implications.

5 Conclusion

Based on this study, PVAc adhesives have a good prospect for the production of LVL-based rubberwood, especially for interior use. Rubberwood LVL produced using PVAc adhesives has a good performance of physical and mechanical properties according to the JAS (Japanese Agricultural Standard 2008) requirement, except for the delamination test. MOE and MOR values of rubberwood LVLs were significantly influenced by the physical treatment, however, neither to horizontal shear strength nor formaldehyde emission. The best performance of LVL resulted from unloaded LVL with the cold-pressed time for 18 h, which upgraded the LVL to 90 E – Special grade, and the values of MOE and MOR were $9,345.05 \pm$

141.61 N mm^{-2} and $80.67 \pm 1.77 \text{ N mm}^{-2}$, respectively. Although the values were not significantly different, the best value of horizontal shear strength that represents LVL bonding strength was obtained from LVL with 18 h cold-pressing time and conditioned with loaded ($13.10 \pm 1.47 \text{ N mm}^{-2}$) and unloaded ($12.23 \pm 1.36 \text{ N mm}^{-2}$) for 7 days. The percentage of delamination values decreased with an increase in the cold-pressing time from 1.5 to 24 h and conditioning time from 7 to 14 days. The lowest value of delamination (19.06%) was obtained from LVL with 24 h cold-pressing time and conditioned with loaded for 14 days. These results indicate that the better performance of LVL seemed in line with an increase in the pressing time and solidification time. However, further studies using cold-pressing time for at least 24 h and conditioned time with loaded treatment more than 14 days could be predicted, which will contribute to improve the delamination performance of the PVAc adhesives. Formaldehyde emission obtained in this research (0.1 mg L^{-1}) met F4S (or F****) classification according to the Japanese Agricultural Standard (2008).

Acknowledgments: The authors would like to be grateful to the Head of Institute for Research and Community Services Institut Teknologi Bandung for the financial support of this research through the International Research Collaboration Program between the School of Life Sciences and Technology, Institut Teknologi Bandung, and Graduate School of Agriculture, Shizuoka University, year 2017.

Conflict of interest: Authors declare no conflict of interest.

References

- [1] Abdurachman, Hadjib N. The quality of some wood of fast tree growing species for building materials based on mechanical properties. Proceeding of PPI Standardization. Jakarta: National Standardization Body; November 19, 2009. p. 1–11. (in Indonesian).
- [2] Alamsyah EM. Studies on Bonding Performance of Fast-growing Wood Species from Tropical Plantation Forest. Doctoral Dissertations. Gifu, Japan: Gifu University, United Graduate School of Agricultural Science, Biological Resources Science; 2008. p. 82–88.
- [3] Andromachi M, Ekaterini R. Adhesive bond performance of heat-treated fir wood (*Abies borrisiiregis*). Wood Res. 2018;63(5):909–16.
- [4] Arruda LM, Del Menezzi CHS. Properties of a laminated wood composite produced with thermomechanically treated veneers. Adv Mater Sci Eng. 2016;2016:9. doi: 10.1155/2016/8458065, Article ID 8458065. Available at (accessed April 14, 2018).

- [5] Aydin I. Activation of wood surfaces for glue bonds by mechanical pre-treatment and its effects on some properties of veneer surfaces and plywood panels. *Appl Surf Sci.* 2004a;233(1):268–74.
- [6] Aydin I, Çolak S, Çolakoglu G, Salih E. A comparative study on some physical and mechanical properties of laminated veneer lumber (LVL) produced from Beech (*Fagus orientalis* Lipsky) and Eucalyptus (*Eucalyptus camaldulensis* Dehn.) veneers. *Holz Roh-Werkst.* 2004b;62(3):218–20.
- [7] Back EL. Oxidative activation of wood surfaces for glue bonding. *For Product J.* 1998;41(2):30–6.
- [8] Bekhta PA Method of the plywood production. Patent of Ukraine, No. 62787A dated 15.12.03. Bulletin No. 12; 2003
- [9] Bekhta PA, Hizioglu S, Shepelyuk OO. Properties of plywood manufactured from compressed veneer as building material. *Mater Des.* 2009;30(4):947–53.
- [10] Bekhta PA, Marutzky R. Reduction of glue consumption in the plywood production by using previously compressed veneer. *Holz als Roh-und Werkstoff.* 2007;65(1):87–8.
- [11] Belfas J, Groves KW, Evans PD. Bonding surface-modified Karri and Jarrah with resorcinol formaldehyde. I. The effect of sanding on wettability and shear strength. *Holz als Roh-und Werkst.* 1993;51(4):253–9.
- [12] Boerhendhy IC, Nancy, Gunawan A. Prospect and potential use of rubber wood as substitution of natural forest wood. *J Tropical Wood Sci Technol.* 2003;1(1):35–46. (in Indonesian).
- [13] Carbas RJC, Marques EAS, da Silva LFM, Lopes AM. Effect of cure temperature on the glass transition temperature and mechanical properties of epoxy adhesives. *J Adhes.* 2014;90(1):104–19.
- [14] Carvalho L, Magalhaes F, Ferra J. Formaldehyde emissions from wood-based panels – testing methods and industrial perspectives. In: Cheng CB, Ln FH, editors. *Chemistry, applications and role in polymerization.* Hauppauge, NY: Nova Science Publishers; 2012.
- [15] Costa NA, Ferra J, Martins J, Coelho C, Pereira J, Cruz P, et al. Impact of thermal treatment on bonding performance of UF/PVAc formulations. *Int Wood Products J.* 2014;5(4):212–6.
- [16] Cowan DA, Blankenhorn PR, Murphey WK. Effects of relative humidity and shelf-life on selected properties of polyvinyl acetate adhesive films. *Wood Fiber.* 1978;10(2):138–46.
- [17] Ding WE, Kader RA, Kawai S. Properties of Rubber wood LVL reinforced with Acacia Veneers. vol. 83. Kyoto, Japan: Wood research: bulletin of the Wood Research Institute Kyoto University; 1996. p. 8–16.
- [18] Esteves B, Pereira H. Wood modification by heat treatment: a review. *Bioresources.* 2009;4(1):370–404.
- [19] Follrich J, Vay O, Veigel S, Müller U. Bond strength of end-grain joints and its dependence on surface roughness and adhesive spread. *J Wood Sci.* 2010;56:429–34.
- [20] Gardner DJ, Elder TJ. Surface activation treatment of wood and its effect on gel time of phenol-formaldehyde resin. *Wood Fiber Sci.* 1988;20(3):378–85.
- [21] Hu W, Guan H. A finite element model of semi-rigid mortise-and-tenon joint considering glue line and friction coefficient. *J Wood Sci.* 2019;65(14):1–9.
- [22] Japanese Agricultural Standard. Japanese agricultural standard for laminated veneer lumber. Notification No. 701. The Ministry of Agriculture, Forestry and Fisheries of Japan; 2008, http://www.maff.go.jp/j/jas/jas_kikaku/pdf/kikaku_tanpan251112.pdf (in Japanese).
- [23] Jelinska N, Kalnins M, Tupureina V, Dzene A. Poly (vinyl alcohol)/poly(vinyl acetate) blend films. *Sci J Riga Technical Univ Mater Sci Appl Chem.* 2010;21:55–61.
- [24] Hashim R, Sarmin SN, Sulaiman O, Yusof LHM. Effects of cold setting adhesives on properties of laminated veneer lumber from oil palm trunks in comparison with rubber wood. *Eur J Wood Wood Products.* 2011;69:53–61.
- [25] Khoo PS, Chin KL, H'ng PS, Bakar S, Lee CL, Go WZ, et al. Physical properties and bonding quality of laminated veneer lumber produced with veneers peeled from small-diameter rubber wood logs. *R Soc Open Sci.* 2019;6:191763.
- [26] Kim S, Kim HJ. Study of miscibility of melamine-formaldehyde resin and poly(vinyl acetate) blends for use as adhesives in engineered flooring. *J Adhes Sci Technol.* 2006;20:209–19.
- [27] Kim S, Kim HJ, Choi YM, Jang SW. Characteristics of non-plasticizer PVAc resin for wood products. *Mokchae Konghak.* 2007;35(2):61–8.
- [28] Kliwon S, Iskandar MI. Processing of small diameter logs for laminated veneer, veneer and plywood production. *Proceeding of the Second International Wood Science Seminar.* Serpong, Indonesia: Indonesian Institute of Sciences; 1998. p. C30–5 (in Indonesian).
- [29] Komarayati S, Setiawan D, Nurhayati T. Chemical analysis and dry distillation of rubber wood (*Hevea brasiliensis* Muell. Arg.). *For Products Res J.* 1995;13(1):1–8. (in Indonesian).
- [30] Konnerth J, Kluge M, Schweizer G, Miljkovic M, Gindl-Altmutter W. Survey of selected adhesive bonding properties of nine European softwood and hardwood species. *Eur J Wood Wood Products.* 2016;74:809–19.
- [31] Král P, Klímek P, Děcký D. Comparison of the bond strength of oak (*Quercus* L.) and beech (*Fagus sylvatica* L.) wood glued with different adhesives considering various hydrothermal exposures. *J For Sci.* 2015;61(5):189–92.
- [32] Li R. Time-temperature superposition method for glass transition temperature of plastic materials. *Mater Sci Eng.* 2000;A278(1):36–45.
- [33] Ministry of Agriculture of Indonesia. Tree crop estate statistics of Indonesia 2018–2020. Jakarta: Secretariate of Directorate General of Estates, Directorate General of Estates; 2019. (in Indonesian).
- [34] Moya R, Rodríguez-Zúñiga A, Vega-Baudrit J, Álvarez V. Effects of adding nano-clay (montmorillonite) on performance of polyvinyl acetate (PVAc) and urea-formaldehyde (UF) adhesives in *Carapa guianensis*, a tropical species. *Int J Adhes Adhesives.* 2015;59:62–70.
- [35] Ordu M, Altinok M, Atilgan A, Ozalp M, Peker H. The effects of heat treatment on some mechanical properties of laminated black pine (*Pinus nigra*). *Int J Phys Sci.* 2013;8(19):1029–35.
- [36] Paris J. Adhesives for paper, board and foils. *Int J Adhes Adhesives.* 2000;20:89–90.
- [37] Rohumaa A. The impact of log preheating on birch veneer surface quality, bond formation and plywood performance [doctoral dissertations]. Helsinki, Finland: Aalto University, School of Chemical Technology, Department of Forest Products Technology; 2016.

- [38] Petkovic G, Vukoje M, Bota J, Preprotic SP. Enhancement of polyvinyl acetate (PVAc) adhesion performance by SiO₂ and TiO₂ Nanoparticles. *Coatings*. 2019;9(707):1–17.
- [39] Shukla S, Kamdem D. Properties of laminated veneer lumber (LVL) made with low density hardwood species: effect of the pressure duration. *Holz Roh-Werkst*. 2008;66(2):119–27.
- [40] Sutrisno, Alamsyah EM, Sulistyawati E, Suheri A. The potential use of wood waste ash nanofiller for improvement of laminated veneer lumber production made from Jabon (*Anthocephalus cadamba*). *J Indian Acad Wood Sci*. 2018;15(2):126–31.
- [41] Sutrisno, Widyorini R, Syamsudin TS, Alamsyah EM, Purwasasmita BS. Bonding strength of plywood bonded using phenol formaldehyde mixed with wood bark powder nanofiller. *J Indian Acad Wood Sci*. 2020;17(1):21–33.
- [42] Uysal B. Bonding strength and dimensional stability of laminated veneer lumbers manufactured by using different adhesives after the steam test. *Int J Adhes Adhesive*. 2005;25(5):395–403.
- [43] Vick CB. *Adhesive Bonding of Wood Materials in Wood Hand Book, Wood as an Engineering Material*. Madison, USA: Forest Products Laboratory; 1999. p. 463.