Laminated Veneer Lumber from Spindleless Rotary-peeled Veneers Produced from Short Rotation, Small *Hevea* Plantation Logs: Effects of Lamination Pressure

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The invention of spindleless lathe technology has enabled veneers to be produced from small logs, such as logs from short rotation *Hevea* plantations, with low recovery loss. However, for structural laminated products, such as laminated veneer lumber (LVL), manufacturers are highly selective regarding the veneers for their conventional production. During the peeling process of small logs (< 18 cm), deeper and higher frequency of lathe checks were induced on veneer surface compared to the common log size used (> 30 cm). In this study, spindleless rotary-peeled veneers made from small rubber logs were processed into LVL using different lamination pressures: 7, 8, 9, and 10 kgf/cm^2. The effects of lamination pressures on the physical and mechanical properties of the produced LVL were evaluated. Based on the findings, the specific gravity increased from 0.73 to 0.83 with increased lamination pressure. In terms of mechanical properties, all the values increased with lamination pressure, but with a sudden drop with 10 kgf/cm^2. Understanding the effect of lamination pressure on the physical and mechanical properties can shed light on optimizing the usage of spindleless rotary-peeled veneers from small logs for the production LVL and other lamination products.

Keywords: Laminated veneer lumber; Small Hevea log; Spindleless rotary-peeled veneers; Lamination pressure; Physical properties; Mechanical properties

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INTRODUCTION

Rubber tree (*Hevea brasiliensis*) is a fast-growing hardwood species that is one of the most important agriculture crops in Malaysia (Teoh *et al.* 2011; Ratnasingam *et al.* 2012). Currently, *Hevea* plantations have been managed under intensive silviculture techniques to achieve a higher yield of latex production within a short-term period with less consideration for the wood yield (Teoh *et al.* 2011). Under such conditions, rubber trees are being felled after 15 years compared to the conventional 25 to 30 years; this practice produces rubber logs with small diameter (Khoo *et al.* 2018). Previous studies have confirmed that rubberwood harvested from a short rotation *Hevea* plantation (15 years old) contains wood properties that are different from rubberwood recovered from a plantation with a longer rotation of 25 to 30 years (Khoo *et al.* 2018). The tree age has a major effect on wood properties, with younger trees having lower wood density, shorter fibers length, smaller lumens, and thinner cell walls (Naji *et al*. 2012; Saffian *et al*. 2014).

Despite these differences, the properties are generally in the range of desirable properties for many processing options and high-value end-products. Indeed, the reduction of some properties (*e.g.,* density) may prove advantageous for some processes and end products. Logs harvested from short rotation *Hevea* plantation are also known to yield relatively small diameter logs that contain a range of defects that affect the efficiency of conventional processing methods and suitability for end products (Khoo *et al.* 2018, 2019).

Rubberwood has been one of the most popular species in the wood industry, particularly for particleboard and fiberboard production (Ratnasingam *et al.* 2012). However, particleboard and fiberboard cannot be considered a total substitute for all purposes because of certain inherent limitations (Kilic *et al.* 2006). Sawmilling and veneer processing remain as the attractive processing options for producing high value-added products. With spindleless lathes, small diameter logs can be processed into veneers (Kamala *et al.* 1999; McGavin and Leggate 2019). Moreover, wood loss is low and veneer production is easy because of the chipless peeling of the logs by the automatic lathe (Kilic *et al.* 2006). This has encouraged the utilization of fast-growing plantation species in the production of layered composite lumber such as laminated veneer lumber (LVL) (Bal 2016). The LVL has been developed as an alternative to solid wood (Çolak *et al.* 2004). This is because LVL makes use of small-sized timber yet is constructed to be stronger than solid wood with similar dimensions (Erdil *et al.* 2009). It is possible to produce lumber with larger dimension and straight structural members using glued-laminated veneer construction (Aydm *et al.* 2004; Kilic *et al.* 2006). Being a homogenous and dimensionally stable building material, LVL can be used where strength, uniformity, and stability are required (Aydm *et al.* 2004; Uysal 2005), accompanied by reduce processing cost, improve stress distributing properties, aesthetic appearances, molding ability, *etc*. (Kilic *et al.* 2006).

However, when fabricating structural laminated products, such as LVL, manufacturers are highly selective regarding the veneers for their conventional production. It was found that during the peeling process of small rubber logs (< 18 cm), deeper and higher frequency of lathe checks were induced on the veneer surfaces compared to the common log size used (> 30 cm) (Khoo *et al.* 2018). Lathe checks lead to a rough surface (Dundar *et al.* 2008), and it was stated by Li *et al.* (2020) that the presence of lathe checks decreases the integrity of bondlines and deepens the adhesive penetration. Due to these reasons, over-penetration can easily happen using veneers peeled from small logs if extensive lamination pressure is applied. However, a study by Khoo *et al.* (2019) claimed that with the presence of higher lathe check frequency, it facilitates the penetration of adhesive for stronger bonding if adequate lamination pressure is applied. During lamination pressing, excessive adhesive will be squeezed out when high pressure applied. Hence, veneer lamination under low pressure will have thicker gluelines, and veneer lamination under high pressure will have very thin gluelines. Both thick and starved gluelines will cause weak joints due to poor bonding. When glueline thickness is within the optimum range, the adhesive will not fail prematurely, as the load transfer is maximized and the creep is minimized (Kurt and Cil 2012).

In LVL manufacturing, adhesive is applied on the tangential surface of the veneer. Hence, porosity is limited and there are fewer pathways in which the adhesive can flow (Vick 1999). Although the presence of lathe checks allows more adhesive penetration, sufficient pressure is still needed to squeeze the adhesive into the wood structure for more effective mechanical interlocking (Li *et al.* 2020). The setting of lamination pressures does not just depend on the type and viscosity of adhesive used but also on the type and physical properties of the veneer (Rabiej and Behm 1992). The application of lamination pressure is often required for the veneer to achieve the required bonding strength. To achieve the highest bonding strength, the adhesive must penetrate and mechanically interlock several cells deep into a sound, undamaged cell structure (Vick 1999). Furthermore, pressure also forces entrapped air from the joint, it brings adhesive into molecular contact with the wood surfaces, it squeezes the adhesive into a thin continuous film, and it holds the assembly in position while the adhesive cures. When pressure is too high, the adhesive can over-penetrate porous woods and cause starved gluelines that are inferior in bond strength (Vick 1999). Conversely, insufficient pressure caused poor localized bonding and increase the blow rate (Vella *et al.* 2017).

In this study, the manufacturing of LVL was completed using rubberwood veneers obtained from small rubber logs using a spindleless lathe. The main objective of this study was to determine the optimum lamination pressure for LVL produced from spindleless rotary-peeled veneers made from small logs from short rotation *Hevea* plantations for timber and latex production. The expectation is that the outputs of this study will contribute to a better understanding of the lamination pressure on the adhesive penetration between veneers with the influence of lathe checks that induced during the peeling of small rubber logs. Understanding the effect of lamination pressure on the physical and mechanical properties can shed light on optimizing the usage of spindleless rotary-peeled veneers from small logs for the production of LVL and other lamination products.

EXPERIMENTAL

Materials

Board preparation

Small-diameter rubberwood logs (between 15 and 18 cm) from short rotation *Hevea* plantations (Kuala Kangsar, Perak, Malaysia) were peeled using a spindleless rotary-peeler (Hk-130; Linyi Hengkai Machinery Manufacture Factory, Shandong, China) according to the method demonstrated by Khoo *et al.* (2018) to produce veneer with 2 mm thickness and the properties are listed in Table 1.

Table 1. Properties of Spindleless Rotary-peeled Veneers (2 mm Thickness) Made of Small Logs from Short Rotation *Hevea* Plantations (Khoo *et al.* 2018)

Lathe Check Properties		Contact Angle (º) after 10 s
Depth (%)	Frequency per 5 cm	
50 ± 15	30 ± 10	8

Spindleless rotary-peeled veneers of 2-mm thickness with a moisture content of 8 ± 2% were used in the manufacture of rubberwood LVL. Phenol formaldehyde (PF) adhesive with 45% solid content was obtained from Aica Chemicals (M) Sdn. Bhd, Negeri Sembilan, Malaysia. Some properties of the PF adhesive were as follows: specific gravity of 1.232 at 30 ℃; pH of 12.90 at 30 ℃; viscosity of 69 cP at 30 ℃, and gel time of 21 min at 105 ℃. Commercial filler (Aica Chemicals (M) Sdn. Bhd, Negeri Sembilan, Malaysia was used with the PF adhesive with the ratio of 1:3. A glue spread rate of 200 g/m² was applied on the veneer surfaces, the veneer sheets were arranged with the grain orientation running in the same direction to the next layer. The loose side of the veneer was placed towards the center of the boards. The seven ply LVLs were subjected to cold press for 5 min and hot press at 120 °C for 10 min with 7, 8, 9, and 10 kgf/cm² lamination pressure (CMV100H-20-BCLPX; Carver, Wabash, Indiana). After hot pressing, the LVLs were conditioned at temperature of 20 ± 3 °C and relative humidity of 65 ± 1% until they reached the equilibrium moisture content of 10 ± 2%. Figure 1 shows the schematic diagram of the rubberwood LVL.

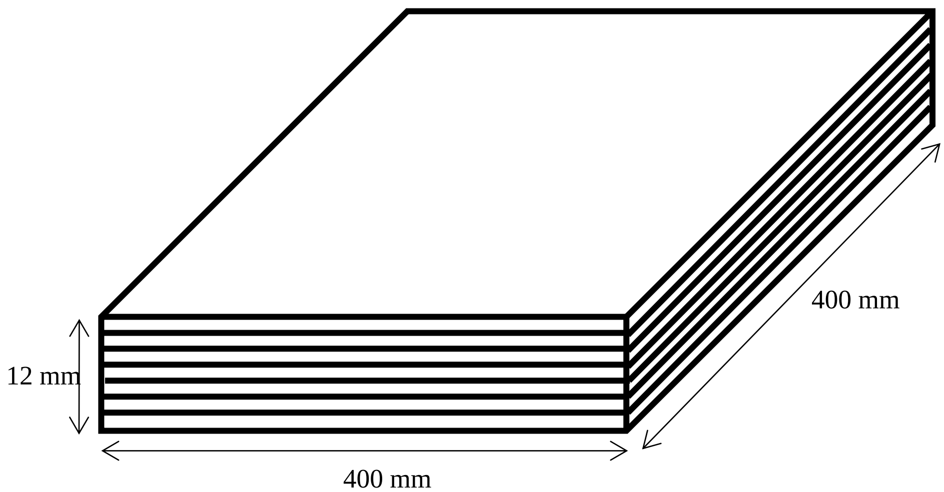

Fig. 1. The LVL with 12 mm thickness comprised of 7 ply of 2-mm-thick veneer

Evaluation

Moisture content and density

The air-dry density of test specimens with dimensions of 50 mm × 50 mm was determined according to ASTM D2395 (2002) by weighing the specimens and measuring the volume of specimens. Density was calculated using Eq. 1:

$$Density\ \left(\frac{kg}{m^3}\right) = \frac{Mass}{Volume} \tag{1}$$

Specific gravity of test specimens was determined by dividing the oven-dry density of the specimens with density of water. Moisture content of the specimens was determined using a conventional drying method according to ASTM D4442 (2003). The specimens were oven-dried at 103 ± 2 °C to constant weight to determine the oven-dry weight. Moisture content of the specimens was calculated as Eq. 2:

$$Moisture\ Content\ (\%) = \frac{Initial\ Weight\ (g) - Oven{-}dry\ Weight\ (g)}{Oven{-}dry\ Weight\ (g)} \times 100 \tag{2}$$

Compression ratio

The compression ratio of the veneer sheets after the hot-pressing process was calculated using Eq. 3,

$$Compression\ ratio\ (\%) = \frac{T_{\mathrm{I}} - T_{\mathrm{f}}}{T_{\mathrm{I}}} x\ 100 \tag{3}$$

where T_{I} is the total thickness (mm) of veneers, T_{f} is the thickness (mm) of the board.

Water absorption and thickness swelling

Test specimens with dimensions of 50 mm × 50 mm were weighed, and the thickness direction was measured before being submerged in distilled water (25 mm below the liquid surface) that was maintained at a temperature of 20 ± 1 °C. After 2 h submersion, the water was removed and the specimens were suspended to drain for 10 ± 2 min to remove excess surface water. The specimens were weighed, and the thickness of the specimens was measured immediately. After that, the specimens were submerged for an additional 22 h and followed by the weighing and measuring procedures mentioned above. After submersion, the specimens were put in an oven at 103 ± 2 °C to calculate the moisture content based on oven-dry weight. Based on ASTM D1037 (2012), the percentage of water absorption and thickness swelling were determined using Eqs. 4 and 5:

$$Water\ Absorption\ (\%) = \frac{Final\ Weight\ (g) - Initial\ Weight\ (g)}{Initial\ Weight\ (g)} \times 100 \quad (4)$$

$$Thickness\ Swelling\ (\%) = \frac{Final\ Thickness\ (mm) - Initial\ Thickness\ (mm)}{Initial\ Thickness\ (mm)} \times 100 \quad (5)$$

Scanning electron microscopy (SEM)

The adhesives' penetration was assessed using a scanning electron microscope (EM-30AX; COXEM, Daejeon, Korea) with an acceleration voltage of 20 kV. Specimens for SEM were taken at the cross-section of each LVL panel.

Static bending

A flatwise and edgewise three-point static bending test was carried out according to the modified ASTM D5456-03 (2003) using a universal testing machine (Bluehill Instron 5567; Instron, Shakopee, USA) on specimens with dimensions of 12 mm thickness × 50 mm width × 316 mm length. The span-to-depth ratio was 18 and a depth-to-width ratio of three or greater needs to be laterally supported. Load applied perpendicular to the grains, and the crosshead loading speed was kept at 1.05 mm/min continuously throughout the test.

Compression strength parallel to the longitudinal axis

Specimen size for compression strength parallel to grain was 12 mm × 20 mm × 60 mm according to modified ASTM D5456 (2003). Load applied in a direction parallel to the grains, and the crosshead loading speed was kept at 0.06 mm/min. The compression strength parallel to the longitudinal axis was calculated using the following formula:

$$Compression\ strength\ (MPa) = \frac{Maximum\ load\ (N)}{Cross{-}sectional\ area\ of\ the\ specimen\ (mm^2)} \quad (6)$$

Tensile strength parallel to the longitudinal axis

Tensile strength parallel to grain was evaluated according to modified ASTM D5456 (2003) on specimens with dimension 12 mm thickness × 25 mm width × 250 mm length. Load applied in a direction parallel to the grains, and the crosshead loading speed was kept at 0.15 mm/min. The tension strength parallel to the longitudinal axis of each specimen was calculated from the following formula:

$$Tensile\ strength\ (MPa) = \frac{Maximum\ load\ (N)}{Thickness\ of\ specimen\ (mm) \times Width\ of\ specimen\ (mm)} \quad (7)$$

Gluebond shear strength

Specimen size for gluebond shear strength was 12 mm × 25 mm × 81 mm according to ASTM D906 (2004). Two grooves of 3 mm wide were made on either side to a depth of two plies and glue shearing area was kept 25 mm × 25 mm. Crosshead loading speed was applied continuously throughout the test at 4 mm/min. This test was carried out using the INSTRON universal testing machine. The shear strength of each specimen was calculated from the following formula,

$$Gluebond\ shear\ strength\ (MPa) = \frac{F}{l \times b} \quad (8)$$

where F is the failing force of the specimen (Newton), l is the length of the shear area (mm), and b is the width of the shear area (mm).

RESULTS AND DISCUSSION

Table 2. Analysis of Variance of the Effect of Lamination Pressure on the Physical and Mechanical Properties of Rubberwood LVLs

Properties	Lamination Pressure (kgf/cm^2)				Pr > F
	7	8	9	10	
Equilibrium Moisture Content (%)	12.83^a (2.06)	12.56^a (1.05)	12.68^a (2.43)	12.62^a (2.26)	0.328$^{n.s.}$
Density (kg/m^3)	779.74^a (3.34)	837.72^{ab} (3.37)	864.11^b (5.79)	874.18^b (4.39)	0.001**
Specific Gravity	0.73^a (3.11)	0.79^{ab} (3.72)	0.83^b (6.34)	0.83^b (4.50)	0.001**
Water Absorption After 2 h (%)	11.13^a (8.21)	9.65^a (10.17)	9.67^a (13.75)	9.54^a (7.86)	0.039*
Water Absorption After 24 h (%)	32.10^a (7.45)	29.81^a (8.78)	28.56^a (9.06)	28.52^a (5.61)	0.049*
Thickness Swelling After 2 h (%)	2.50^a (17.42)	2.70^a (9.96)	2.59^a (17.36)	2.79^a (15.17)	0.615$^{n.s.}$
Thickness Swelling After 24 h (%)	4.19^a (12.31)	5.44^b (11.72)	4.93^{ab} (23.30)	5.42^b (9.50)	0.029*
MOR in Flatwise Direction (MPa)	72.97^a (1.83)	84.95^b (4.26)	91.05^b (1.42)	88.44^b (2.96)	0.000**
MOE in Flatwise Direction (MPa)	7519.56^a (9.82)	8176.09^a (11.01)	11189.50^b (0.89)	10074.30^b (5.89)	0.000**
MOR in Edgewise Direction (MPa)	47.62^a (1.64)	47.55^a (2.30)	51.52^b (2.51)	49.49^{ab} (1.97)	0.005**
MOE in Edgewise Direction (MPa)	1154.59^a (9.53)	1203.90^a (6.76)	1249.80^a (3.08)	1238.74^a (6.84)	0.526$^{n.s.}$
Compression Strength Parallel to the Longitudinal Axis (MPa)	43.83^a (4.32)	45.85^{ab} (5.36)	50.23^c (0.79)	49.25^{bc} (0.45)	0.003**
Tensile Strength Parallel to the Longitudinal Axis (MPa)	50.59^b (3.94)	40.12^a (5.14)	50.38^b (5.17)	42.70^a (1.46)	0.000**
Gluebond Shear Strength (MPa)	5.15^{ab} (8.14)	5.72^b (3.79)	6.46^c (4.38)	4.72^a (2.21)	0.000**

Modulus of rupture (MOR); Modulus of elasticity (MOE)

Means followed by the same letters in the same column are not significantly different at P ⩽ 0.05 according to Tukey's test; Values in parentheses indicate coefficient of variance; n.s.: not significant; *: significant at p < 0.05; **: significant at p < 0.01

According to analysis of variance (ANOVA), the effect of lamination pressure on air-dry density, specific gravity, and mechanical properties were highly significant ($p < 0.01$). Moreover, the effect of lamination pressure on the percentage of water absorption and thickness swelling were significant ($p < 0.05$). The average values that were significant were compared using Tukey's test and are summarized in Table 2.

Compression Ratio

After conditioning for two weeks, the final thickness of LVL pressed with 7, 8, 9, and 10 kgf/cm^2 lamination pressure decreased by 12.1, 13.2, 14.8, and 15.5% relative to the initial thickness of 7 ply 2-mm rubberwood veneers, respectively (see Fig. 2). The LVL thickness reduction correlated well to the respective degree of densification. The densification of rubberwood LVL was influenced by the lamination pressure. The densification increased with increased lamination pressure, accompanied by LVL thickness reduction. Similar results were reported by Unsal *et al.* (2011), Kurt and Cil (2012), and Bal (2016). The final LVL thicknesses ranged between 11.83 to 12.30 mm. No excessive compression was expected in this study because the compression ratio for every LVL was less than 16% compared to previous research by Wang and Dai (2005), who reported that an excessive compression ratio ranged above 16%. The LVL pressed with 9 kgf/cm^2 lamination pressure had the nearest thickness to the targeted thickness (12 mm), followed by LVL pressed at 8, 10, and 7 kgf/cm^2 lamination pressure.

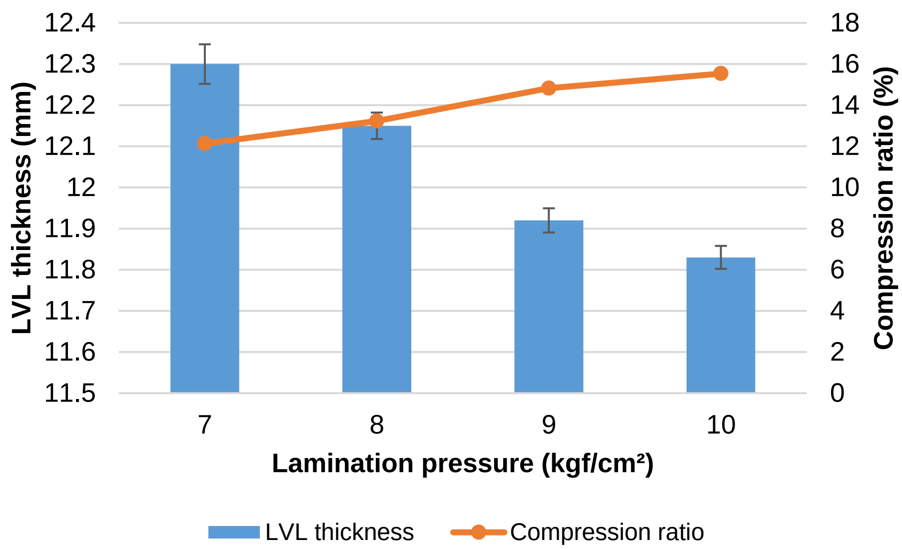

Fig. 2. Compression ratio and final thickness of rubberwood LVL with 7, 8, 9, and 10 kgf/cm^2

Density and Moisture Content

As shown in Table 2, the equilibrium moisture content of the rubberwood LVL was within a narrow range between 12.5 and 12.9% after being conditioned for two weeks. The density of rubberwood LVLs ranged from 780 to 875 kg/m^3, which was higher than rubberwood density reported by Khoo *et al.* (2018) by 20 to 24%. The density of rubberwood LVL was higher because of the lamination pressure applied during the hot-pressing process (Kurt *et al.* 2011; Bal and Bektaş 2012a). Densification reduces the space of the woods' cells and the distance between cellulose chains in cell wall structures, which cause permanent deformation in wood's cell wall during hot pressing (Unsal *et al.* 2011).

Furthermore, the reduction of the total LVL volume with the addition of adhesive also contributes to the density of rubberwood LVL (Shukla and Kamdem 2009; Sulaiman *et al.* 2009) other than densification. The density of PF adhesive used in this study was 1.2 g/m^3, which much higher than density of rubberwood.

The analysis of variance results showed that the rubberwood LVL pressed with 9 and 10 kgf/cm^2 lamination pressure obtained the highest density. During the hot-pressing process, rubberwood LVL was pressed perpendicular to the glueline. When temperature and pressure is applied, some densification of the veneers in LVL is expected (Kurt and Cil 2012). The density of rubberwood LVL is actually dependent on the weight and volume itself. Higher lamination pressure results in higher compression ratio and densification; hence there is a reduction in LVL thickness. The reduction of the thickness and volume of rubberwood LVL with a high lamination pressure produced a rubberwood LVL with higher density. The effect of lamination pressure on specific gravity was highly significant ($p < 0.01$). Specific gravity was increased with increased lamination pressure. As mentioned earlier, densification caused by high lamination pressure reduced the void volume in woods' cells. Woods with lesser pores and void volume generally have higher specific gravity (Vick 1999).

Water Absorption and Thickness Swelling

The lamination pressure had a significant ($p < 0.05$) effect on water absorption after 2 and 24 h and thickness swelling after 24 h. At the end of the 2- and 24-h immersion, rubberwood LVLs pressed with 10 kgf/cm^2 lamination pressure had the lowest percentage of water absorption and greatest percentage of thickness swelling. As the lamination pressure increased, the water absorption rates of the LVL decreased, while the thickness swelling rates increased. The rate of water absorption in wood normally depends on the rate at which air can escape from wood. As wood absorbs water above fiber saturation point, air in the cell lumina is replaced by water (Vick 1999). Lowest water absorption properties were observed in LVL pressed with 10 kgf/cm^2 pressing pressure. This was due to the lumen of the woods' cells being compressed and the distance between cellulose chains in cell wall structures being reduced (Unsal *et al.* 2011). The pathway for water-air exchange was disrupted because of the densification. Hence, a low percentage of water absorption was achieved with increasing compression ratio and densification due to increasing lamination pressure. In addition, Kurt and Cil (2012) reported that deeper adhesive penetrations in relation to higher lamination pressure may also contribute to a lower percentage of water absorption.

In terms of thickness swelling after 24 h immersion, the highest percentage was recorded for rubberwood LVL pressed at 8 and 10 kgf/cm^2 lamination pressure, and the differences were significant ($p < 0.05$). Unsal *et al.* (2011), Kurt and Cil (2012), and Bal (2016) claimed that a higher percentage of thickness swelling was recorded for LVL pressed at higher lamination pressure. The reason for this result is the effect of lamination pressure on the compression ratio and densification. Higher compression ratio implies that more compressive deformation was imparted onto the panel during hot pressing and the fibers are under severe compaction (Wong *et al.* 1999). Compressive stresses were built up in panels especially in the thickness direction. When a panel comes in contact with water, the compressive stresses are released (Wong *et al.* 1999; Shukla and Kamdem 2009). As the compression ratio increased due to the increasing of lamination pressure, the thickness swelling of the rubberwood LVL increased. This phenomenon is known as spring-back effect (Unsal *et al.* 2011), which is greatly controlled by the lamination pressure. Higher lamination pressure in hot pressing causes a greater amount of spring-back. Moreover, rubberwood LVL pressed with 10 kgf/cm^2 swelled more than 7 kgf/cm^2, which was expected due to the density of LVL after being pressed. It is well known that higher density wood swells more than lower density wood (Uysal 2005; Bal 2016).

Flexural Strength

Based on Table 2, the lamination pressure had highly significant effects on flatwise modulus of rupture (MOR) and modulus of elasticity (MOE), as well as edgewise MOR ($p < 0.01$). However, there was no significant effect on edgewise MOE. The MOR and MOE values increased with increased lamination pressure. This can be explained by an increase in density with increasing lamination pressure, which resulted in higher MOR and MOE values. Bal and Bektaş (2012a) reported that there is a strong positive relationship between flexural strength and the density of wood-based composites. This was agreed by Shukla and Kamdem (2008) and Kurt and Cil (2012), who mentioned that density is a good predictor of strength properties for wood-based composites. Mechanical properties of LVL can be enhanced through densification (Kurt and Cil 2012). However, there was a slight decrease in MOR and MOE value when 10 kgf/cm^2 was used. This may explain the excessive resin penetration into lathe checks when high lamination pressure was applied during the hot-pressing process. This will lead to the formation of a starved glueline and reduction of bonding strength. An insufficient or incomplete glueline will affect the ability of stress transferring from top to bottom of the LVL during flexural testing; thus, stress will develop between the veneer layers. In order to allow stresses to transfer efficiently, an optimum adhesive penetration is needed to provide better mechanical interlocking interaction with several cells deep into a sound, undamaged cell structure (Vick 1999). Optimum glueline thickness allows stress transfer between laminates efficiently and exhibits better bonding strength (Kurt and Cil 2012). Application of 9 kgf/cm^2 lamination pressure improved the flatwise MOR and MOE by up to 24% and 48%, respectively.

Moreover, the MOE and MOR values were greater in the flatwise direction than in the edgewise direction. The important reason for this discrepancy was the pressing direction. Similar results were reported by Wang and Dai (2005), Bal and Bektaş (2012a, 2012b), and Bal (2014, 2016). This is because of the effects of press pressure applied in the flatwise direction during the hot-pressing process for LVL. Therefore, densification occurs when linear density increases in the flatwise direction (Bal and Bektaş 2012a). During flexural testing, there were three zones on the specimens, which were compression zone, neutral axis, and tension zone. Initially, compression occurred on the fibers located on the top part of specimen while tension occurred on the fibers located at the bottom part of the specimen. Breaking occurred at the bottom surface of the tension zone. When the test was conducted in the flatwise direction, the bottom surface of the specimens were being forced and the rupture occurred. Thus, the stronger the bottom surface veneer was, the greater the bending strength became. In the edgewise direction, all of the veneers acted together. Firstly, the bottom edge of the LVL ruptured. Then, continuing the test resulted in the rupture of the entire specimen (Bal 2016). Concerning this issue, Wang and Dai (2005) stated that the edgewise MOE and MOR values depended on the MOE value of each constituent veneer plies, whereas the flatwise bending strength properties were dominated by the MOE values of the bottom face veneers.

Gluebond Shear Strength

In terms of gluebond shear strength, the highest gluebond shear strength was obtained for rubberwood LVL pressed with 9 kgf/cm^2 lamination pressure, and the differences were highly significant ($p < 0.01$). As shown in Fig. 3, gluebond shear strength for rubberwood LVL increased with lamination pressure. However, there was a sharp decrease in the gluebond shear strength for rubberwood LVL pressed with 10 kgf/cm^2 lamination pressure. This might be due to the over-penetration of adhesive into lathe checks when too high lamination pressure was applied. Only a small amount of adhesive remained in the glueline; hence reducing the glueline capacity to withstand the shear stresses that concentrates the panel and results in higher amounts of glueline failure (Darmawan *et al.* 2015). A second assessment of gluebond quality was made by visual examination of the percentage of wood failure in the shear area of the test specimen after mechanical failure. The trend of percent wood failure was similar with the trend of gluebond shear strength. The percentage of wood failure for LVL pressed with 7, 8, 9, and 10 kgf/cm^2 lamination pressure was 17, 50, 83, and 67%, respectively. Lower wood failure (less than 50%) was observed from samples pressed using 7 and 8 kgf/cm^2. Insufficient lamination pressure caused poor adhesive penetration, which was clearly shown from the delamination of samples with low percentage of wood failure. According to the Voluntary Product Standard PS 1-09 (2010), the product standards for structural panels requires high wood failure values (80% or above) when bonded with an exterior resin-adhesive such as phenol formaldehyde. The LVL should be pressed with pressure 9 kgf/cm^2 to obtain higher penetration of resin and good bonding quality, and thereby, a high percentage of wood failure.

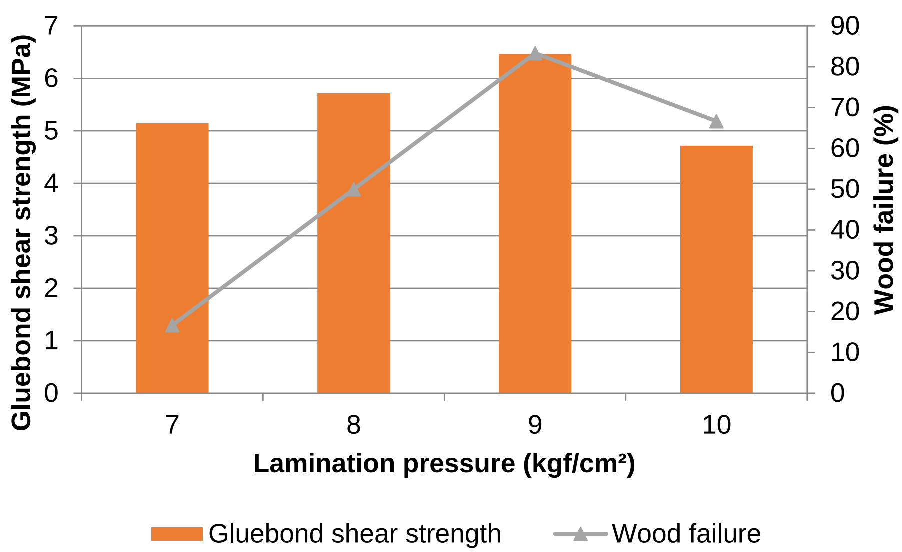

Fig. 3. Gluebond shear strength for rubberwood LVL pressed with 7, 8, 9, and 10 kgf/cm^2

Compression Strength Parallel to the Longitudinal Axis

The compression strength of LVL ranged from 43.8 to 50.2 MPa with coefficient of variance (COV) below 6%. A low COV meant that variability of compression strength was low. According to the variance analysis in Table 2, the lamination pressure had a highly significant effect ($p < 0.01$) on compression strength parallel to the longitudinal axis. The compression strength was increased with increasing lamination pressure, but only up to 9 kgf/cm^2 lamination pressure. A slight reduction of compression strength was seen for the rubberwood LVL produced with 10 kgf/cm^2 lamination pressure. Compression strength reduction of LVL pressed with 10 kgf/cm^2 lamination pressure was due to poor bonding between veneer plies. When the lamination pressure was too high, most of the adhesive might over-penetrate the wood. Thus, glueline thickness would decrease with increasing lamination pressure. In this case, starved joints will be formed and a low bonding strength can be obtained (Kurt and Cil 2012). This explanation was in agreement with Vick (1999), who stated that both starved and thick gluelines result in poor bonding.

Tensile Strength Parallel to the Longitudinal Axis

The effect of lamination pressure on tensile strength parallel to the grain was highly significant ($p < 0.01$). The range of tensile strength obtained was 40.1 to 50.6 MPa. This result was higher compared to those from other studies using poplar and rubberwood with the value of 31.5 MPa (Yue *et al*. 2019) and 29.6 MPa (Yeoh *et al*. 2005), respectively. From the assessment of shear bond test, a low percentage of wood failure for samples pressed with 7 kgf/cm^2 revealed the failure of the lamination. Although, the rubberwood LVL pressed with 7 kgf/cm^2 lamination pressure had the highest tensile strength, the result was considered not valid as the poor adhesive penetration created a separate layer of adhesive in the form of a thick glueline without a strong interlock with the wood. This thick glueline was expected to contribute to the total tensile strength parallel to the longitudinal axis. In a study conducted by Das *et al.* (2020), the phenol formaldehyde specimen without fiber loading exhibited higher tensile strength than the specimen with fiber loading.

As the lamination pressure increased, adhesive penetrated deeper into wood cell structure. Although the glueline thickness decreased, an increase in tensile strength of LVL pressed with 9 kgf/cm^2 was observed. This may be due to the crosslinking between the hydroxyl groups of wood and the formaldehyde moiety of the adhesive as an adhesive-bonded joint was formed. The strength of the chain is determined by the individual link of wood, adhesive, and the interphasing region (Paridah *et al.* 2002). The strength of the crosslinking allows the stress to transfer from one component to another effectively.

Scanning Electron Microscopy

Figure 4 shows the microstructures of veneer lamination under different pressing pressure. The main function of the lamination pressure in this study was to produce a thin glueline, squeeze out excessive PF, and increase the penetration of the PF into veneer and to position the veneers. With the pressure applied, the adhesives were able to penetrate into a few cells above and below the glueline and filled up the lumina area. Hence, more mechanical interlocking interaction between veneers and adhesive is formed when higher lamination pressure was applied (Vick 1999).

The peeling process of small logs produced veneer with a considerable number of lathe checks. After pressing, the lathe checks were closed during the lamination process especially near the glueline except for the specimens from the lowest lamination pressure (7 kgf/cm^2); the lathe checks were still visible as shown in Fig. 4(a). Lathe checks were less visible in specimens applied with lamination pressure of 10 kgf/cm^2 as the length and size of the lathe checks were noticeably decreased with the high lamination pressure. Fang *et al.* (2012) also reported on lathe checks conglutination on veneers due to the effect of high pressing pressure. Lathe checks on veneers were smaller as the pressure increased, which was due to the result of the plasticization of the veneer taking place under both high pressures and high temperatures of densification (Bekhta *et al.* 2012).

As the lamination pressure increased, the dimensions of vessels decreased and the fibers and lumina near the glueline were compressed (Fig. 4). This reduces the total volume of the rubberwood LVL and increases the density (Sulaiman *et al.* 2009). However, as the lamination pressure increased to 10 kgf/cm^2, the lumina located above and below the glueline were found to be over-compressed with high amount of cells collapsed, which caused deformation in the vessels (Fig. 4(d)). This could be the reason why sudden decreased gluebond strength was observed when 10 kgf/cm^2 lamination was applied. The lamination pressure significantly changed the morphology of the veneer, buckling the cell walls and reducing the volume of void spaces. A smooth surface could be seen near the glueline with most of the lumina enclosed and cells collapsed due to the high pressure applied. Some authors claimed that the type and amount of cell collapse has an important effect on the mechanical and physical properties of the densified material (Navi and Girardet 2000; Kutnar *et al.* 2009).

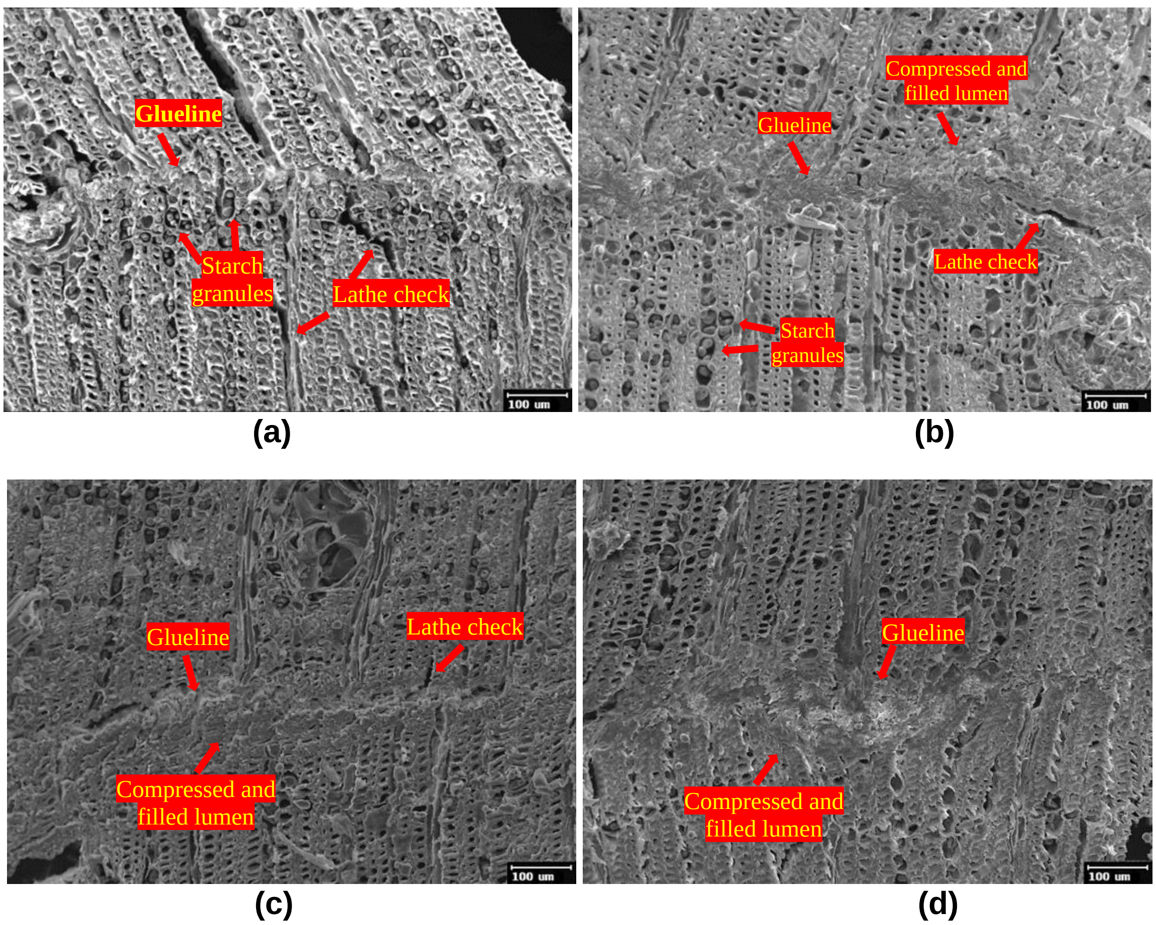

Fig. 4. Rubberwood LVL showing the glueline observed using SEM; LVL hot pressed at (a) 7 kgf/cm^2; (b) 8 kgf/cm^2; (c) 9 kgf/cm^2; and (d) 10 kgf/cm^2 with 200x magnification

The results for the size of the vessels confirmed the fact that the density of wood was increased by reducing the void volume. The fiber lumen diameters of the veneers applied with higher pressure were much less than that of the veneers applied with lower pressure. As evident from the microscopic images, not only was there a size reduction in the cavity vessels, but the cell walls also compressed. The starch granules in the cells can still be clearly seen in specimens applied with lamination pressure of 7 kgf/cm^2 and 8 kgf/cm^2 (Fig. 4 (a to b)), while higher lamination pressure caused most of the cells collapsed and the starch granules are no longer visible (Fig. 4(c to d)).

CONCLUSIONS

1. An increase in lamination pressure from 7 kgf/cm^2 to 9 kgf/cm^2 resulted in an average increase of density, specific gravity, MOR and MOE, compression parallel to the longitudinal axis, and gluebond shear strength. However, a further increased in lamination pressure to 10 kgf/cm^2 did not further contribute to the improvement of mechanical properties.
2. A higher lamination pressure caused most of the cells to collapse and reduction of void volume, thus, increasing the LVL density and reduced the board thickness.
3. As the lamination pressure increased, the water absorption rates of the LVL decreased while the thickness swelling rates increased.
4. The percentage of wood failure in the shear area for LVL pressed with 7, 8, 9, and 10 kgf/cm^2 lamination pressure were 17, 50, 83, and 67%, respectively. Insufficient lamination pressure caused poor adhesive penetration that was clearly shown from the delamination of samples with low percentage of wood failure.
5. The peeling process of small logs produced veneer with a considerable number of lathe checks. With sufficient lamination pressure (9 kgf/cm^2), most of the lathe were enclosed during lamination process.
6. Understanding the effect of lamination pressure on the physical and mechanical properties can shed light on optimizing the usage of spindleless rotary-peeled veneers from small logs for the production LVL and other lamination products.

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