EFFECTS OF PRESS PRESSURES ON GLUE LINE THICKNESS AND PROPERTIES OF LAMINATED VENEER LUMBER GLUED WITH PHENOL FORMALDEHYDE ADHESIVE

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The effects of press pressure on glue line thickness (GLT) and properties of laminated veneer lumbers (LVLs) manufactured from half-round sliced I-214 hybrid poplar clone veneers with phenol formaldehyde adhesives were determined. The results showed that press pressures significantly influenced GLT and properties of LVLs. Results of higher specific gravity, thickness swelling ratio, and mechanical properties, but lower GLT and water absorption ratio were attributed to higher press pressure uses. Optimum properties were obtained by using a press pressure of 10 kg cm^{-2} in relation to GLT and properties of LVLs. Significant relationships were found between GLT and mechanical properties. GLT may provide reliable information to determine wood bonding quality and may be used for non-destructive evaluation of mechanical properties of wood composites in the future.

Keywords: Laminated veneer lumber (LVL); Phenol formaldehyde (PF); Populus x euramericana; Press pressure; Glue line thickness

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INTRODUCTION

Structural composite lumber (SCL) products are characterized by smaller pieces of wood (*i.e.* veneer, veneer strand, wood strand) glued together into sizes common for solid-sawn lumber (Cai and Ross 2010). Laminated veneer lumber (LVL) is one of the most known and commercially produced SCLs that can be defined as a material, manufactured by gluing with structural adhesives and pressing under heat (depending on the type of adhesive) rotary peeled veneers with their grains parallel to each other (Kurt *et al.* 2012). The selection of the type, quality, and quantity of adhesives for manufacturing LVL depends on the end use, exposure conditions, manufacturing conditions, present technology, equipment, dimensions, treatment, and design requirements (Kurt 2010a). Usually, phenolic adhesives (phenol formaldehyde (PF) and phenol resorcinol formaldehyde (PRF)) are used in LVL manufacturing for structural applications in exterior conditions (Kurt 2010b).

Hot-pressing is one of the primary factors in the manufacture of LVLs that affects the strength and quality of the bond line (Kairi 2002). Heat, pressure, and moisture content are the three main parameters governing the mechanisms involved in hot-pressing (Tabarsa 1995). Press pressures depend on the type of adhesive, its viscosity, pressing temperature, surface characteristics (Baumann and Marian 1961), and physical properties of the wood (Rabiej and Behm 1992).

The press pressure influences penetration of adhesives because it is the driving force for hydrodynamic flow (Brady and Kamke 1988). The pressure applied on the adhesive will force it to spread and penetrate into porous, fibrous materials and into the roughness of the surfaces (Cognard 2005). The bond quality is affected by the amount of adhesive penetration into wood substrate during manufacture of wood composites *i.e.* LVLs (Scheikl 2002). An optimum adhesive penetration is needed to repair processing damage of the wood surface, allow better internal surface contact for chemical bonding or interlocking, and stress transfer between laminates (plies) (Scheikl 2002), promote more efficient use of the adhesive (Johnson and Kamke 1992), and provide a reliable glue line thickness (GLT).

The press pressure is one of the main factors to control the GLT in addition to adherent, adhesive, machining, and adhesive spreading. GLT should be controlled because it directly affects the strength of wood composites. One of the most important reasons for the occurrence of a thick glue line is insufficient pressure in the manufacturing process (Kurt 2006). Generally, thick glue lines of many common adhesives lack strength (Bellosillo 1976). Pressure must be applied uniformly and adequately because synthetic resin based structural wood adhesives (*i.e*. PF) are not able to form strong bonds in thick and variable thickness glue lines due to their low viscosity (Vick 1973).

The GLTs for wood joints are generally between 0.127 and 0.178 mm (Kurt 2003). Thicknesses below this range may occur in wood-based products in which high pressure and heat are used, such as LVLs (Kurt and Cil 2012). Optimum press pressures should be determined in relation to GLT. In low-density woods, high pressure forces the adhesive so deeply into the wood that there is insufficient adhesive to fill the bond-line, and it may cause over-penetration and inferior bond strength (Frihart and Hunt 2010). On the other hand, low-pressure causes a decrease in shear strength, does not provide close contact between the surfaces, and glue line remains partly poor (Suomi-Lindberg *et al*. 1986; Kairi 2002).

Unlike the many reports dealing with effects of press pressures on properties of wood composites, research dealing directly with the effect of GLT in relation to press pressures on properties of wood composites with different adhesives has been limited. The main objective of the present research was to determine the effect of five different press pressures (2.5, 5, 7.5, 10, and 12.5 kg cm^{-2}) on GLT, as well as selected physical and mechanical properties of LVLs manufactured from half-round sliced veneers I-214 veneers, glued with the PF adhesive under laboratory conditions. Press pressures below 2.5 kg cm^{-2} were found inadequate relative to the density and bonding quality of LVLs; thus 2.5 kg cm^{-2} was taken as a control press pressure. It was also aimed to determine the optimum press pressure in relation to GLT and properties of LVLs. The relationships between GLT/specific gravity (SG) and mechanical properties of LVLs were also studied.

MATERIALS AND METHODS

Wood Veneers

The LVLs were manufactured using half-round sliced *Populus x euramericana* (I-214) veneers. Veneers were dried to a moisture content of 6 to 8% and shipped to a manufacturing site. They were clipped into dimensions of approximately 600 mm x 150 mm x 3 mm thickness.

Adhesive

A commercial PF adhesive was used. PF adhesive has a pH of 11.50 with a viscosity of 400 cps, a solid content of 47±1%, and specific gravity of 1.21 at 20 ^{o}C (Polisan 2012). The adhesive spreading rate was 200 g m^{-2}, and it was held constant for all press pressures. The gram weight pick up was calculated in accordance to ASTM D899 (1994).

LVL Manufacturing

To manufacture experimental eight-ply LVLs, adhesives were spread on veneers' surfaces and they were immediately assembled with their tight sides facing out on each veneer and with their grain directions parallel to each other. Billets were hot-pressed at a temperature of 140 °C for 30 min and pressure of 2.5 to 12.5 kg cm^{-2}. They were further cut in accordance with specific test dimensions and conditioned at a relative humidity of 65±1% and a temperature of 20±3°C until they reached the equilibrium moisture content of 10±2%.

Testing

Moisture content (MC), SG, dimensional stability (thickness swelling (TS), and water absorption (WA) (24 hours)), modulus of rupture (MOR), modulus of elasticity (MOE), and compression strength (CS) (parallel to grain) values of LVLs were determined in accordance with TS 2471 (1976a), TS 2472 (1976b), TS 3639 (1988), TS 2474 (1976c), TS2478 (1976d), and TS 2595 (1977), respectively. Dimensions of specimens are given in Table 1. LVLs were tested flat-wise to failure in bending under center point loading to determine MOR and MOE. The span-to-depth ratio was fixed to 15 and adjusted for each specimen due their thickness differences as a result of using different press pressures. MOR, MOE, and CS specimens were tested using a Zwick Roell (Z010) testing machine (Zwick, Germany). Thirty replicates were used to test each property.

Table 1. Dimensions of Specimens for Specified Tests

Test	Dimensions (mm)
Oven-dry specific gravity (SG) Moisture content (MC)	Thickness x 20(w) x 30(l)
Thickness Swelling (TS) Water Absorption (WA)	Thickness x 100(w) x 100(l)
Modulus of rupture (MOR) Modulus of elasticity (MOE)	Thickness x 20(w) x 360(l)
Compression strength parallel to grain (CS)	Thickness x 20(w) x 30(l)

GLTs of each specimen were measured with an image analysis technique using a light microscope (Soif SZM45-B2) and recorded to the nearest 0.001 mm. GLTs of all SG/MC, MOE/MOR, and CS specimens were measured. A total of 12 measurements were made (six on each side) in the middle glue line (between 4th and 5th plies and were averaged for each specimen). For each group, GLT was calculated using an average of

1080 measurements (three different properties testing (SG/MC, MOE/MOR, and CS) x 30 specimens x 12 measurements). To explain the strength increases of LVLs compared to corresponding solid woods' (SWs') properties, a compaction factor (*CF*) was calculated according to Bao *et al*. (2001). *CF* can be expressed as,

$$CF = D_L / D_S \quad (1)$$

where D_L is LVL's SG and D_S is SW's SG. The SG of SW's was found 0.34. The *CF* value is used to determine the degree of compaction or densification.

Statistical Analysis

The effects of press pressure on GLT and properties of LVLs were determined by analysis of variance (ANOVA) using the SAS statistical package program (SAS Institute 2001). The resulting F-value was compared to the tabular F-value at the 95% probability level. When there was a significant difference, comparisons between means were made by the Bonferroni t-test. Also, relationships between GLT/SG and mechanical properties were analyzed.

RESULTS AND DISCUSSION

GLT, SG, TS, WA, MOR, MOE, and CS of LVLs were evaluated, and the results are summarized in Table 2 along with the values of respective press pressures. Statistical analysis shows that the difference in all mean values was observed when different press pressures were used (α = 0.05). A Bonferroni t-test result is given for each property separately. MC values were found to be 10 ± 2%.

Table 2. Properties of the Tested LVL Specimens *

Properties	Press Pressure (kg cm^{-2})				
	2.5	5	7.5	10	12.5
GLT (mm)	0.141 **A** (0.007)	0.121 **B** (0.006)	0.088 **C** (0.005)	0.068 **D** (0.006)	0.047 **E** (0.003)
SG	0.35 **D** (0.02)	0.36 **CD** (0.01)	0.38 **C** (0.01)	0.40 **B** (0.02)	0.44 **A** (0.03)
TS (%)	2.61 **D** (0.19)	3.78 **C** (0.37)	4.40 **C** (0.44)	5.09 **B** (0.46)	6.92 **A** (0.88)
WA (%)	67.88 **A** (5.27)	56.34 **B** (3.27)	55.87 **BC** (3.38)	54.72 **BC** (4.96)	50.95 **C** (3.90)
CF	1.09	1.13	1.19	1.25	1.38
MOR (MPa)	54.23 **A** (9.36)	60.65 **AB** (9.15)	62.54 **B** (8.15)	63.88 **BC** (8.66)	69.15 **C** (9.39)
MOE (MPa)	5339.73 **A** (489.31)	5496.22 **AB** (284.59)	5818.76 **BC** (618.71)	5946.67 **C** (542.76)	6211.73 **C** (744.83)
CS (MPa)	63.60 **A** (9.58)	71.00 **B** (10.42)	73.11 **C** (5.86)	80.05 **C** (6.54)	89.41 **D** (9.26)

* Glue line thickness (GLT), specific gravity (SG), thickness swelling (TS), water absorption (WA), compaction factor (*CF*), modulus of rupture (MOR), modulus of elasticity (MOE), and compression strength parallel to grain (CS); Bonferroni t-test (Bon) groupings are given in bold capital letters; means with the same letter are not significantly different. Standard deviations are given in parenthesis.

Higher SG, TS, and mechanical properties, but lower GLT were developed as a result of using higher press pressures. Press pressures above 10 kg cm^{-2} resulted in a very sharp increase in SG, TS, MOR, MOE, and CS. It was not possible to manufacture LVLs beyond the press pressure of 12.5 kg cm^{-2} due to an over-penetration or a starvation problem. Over-penetration is especially common in low-density woods, *i.e.* poplar (Frihart and Hunt 2010). A large portion of the resin might penetrate into the wood, causing a starved glue line because of the following reasons: the viscosity or the degree of condensation of the resin is too low (Dunky 2003) and/or the press pressure is too high. In such a case, a glue line cannot be formed and hence no bonding strength can be obtained (Dunky 2003). The spreading rate of adhesive is found satisfactory for press pressures of up to 12.5 kg cm^{-2}.

The mean GLT values of LVLs fell within a wide range, between 0.047 and 0.141 mm (Table 2). The results proved that the press pressure affected GLT significantly, and there is a strong relationship between GLT and press pressures with coefficient of determinations (R^2) of 0.96. Increasing press pressures resulted in decreasing GLT. The percentage of GLT reduction ranged from a low of 14.18 to a high of 66.67 percent compared to that of the press pressure of 2.5 kg cm^{-2}. The largest reduction in GLT was found in LVLs pressed at 12.5 kg cm^{-2} press pressure. When a press pressure of more than 7.5 kg cm^{-2} was used, GLT decreased at a greater rate than normal (14% per interval).

A very strong linear correlation was found between GLT and MOR, MOE, and CS with R^2 values of 0.91, 0.99, and 0.92, respectively. As press pressures increased, GLT decreased since the degree of glue penetration into the substrate is affected by the amount of press pressure. An optimum adhesive penetration is needed to repair processing damage of the wood surface and to allow better stress transfer between laminates (plies) (Scheikl 2002); thus higher mechanical properties would be possible. Lowest mechanical properties are obtained when the thickest GLT is present. Similar findings were found by Kurt and Cil (2012). GLTs and ratio of mechanical properties decrease were different due to different adhesives use. Adhesives' bond formation and bond performance properties are different.

The mean SG values of LVLs fell within a wide range, *i.e*. 0.35 to 0.44 (Table 2). A strong relationship was found between SG and press pressures with an R^2 of 0.95. The amount and duration of press pressure determine the formation of the density (Pichelin and Dunky 2002). Application of high press pressures may provide better, more thorough interlocking of the resin; thus strong bonds between the veneers can be achieved (Huang 2011). The results showed that it is possible to improve mechanical properties of LVLs through densification. Strong linear correlations were found between SG and MOR, MOE, and CS, with R^2 values of 0.87, 0.95, and 0.97, respectively. A trend of increasing SG accompanied the increase in mechanical properties. LVLs that were manufactured using the highest press pressure of 12.5 kg cm^{-2} had the highest SG and mechanical properties followed by the press pressures of 10, 7.5, 5, and 2.5 kg cm^{-2}. The results were in agreement with Örs *et al.* (2001) and Kurt and Cil (2012), whose studies were related to the effect of press pressure on some mechanical properties of plywood and LVLs bonded with melamine urea formaldehyde adhesive, respectively.

The *CF* values of LVLs fell within a wide range, between 1.09 and 1.31. The *CF* values increased with increased press pressures. The critical press pressure would appear to be above 10 kg cm^{-2}, where the *CF* value increased by 20.18%. Similar findings were found by Kurt and Cil (2012). Press pressure of 12.5 kg cm^{-2} caused the largest degree of compaction. Excessive press pressure use is the main cause of compression of the wood beyond its proportional limit (Marra 1980) at the press pressure of 12.5 kg cm^{-2}.

The test results showed that MOR, MOE, and CS increased by 27.51%, 16.33%, and 40.58%, respectively, at the press pressure of 12.5 kg cm^{-2}. The press pressure of 12.5 kg cm^{-2} resulted in a very sharp increase of mechanical properties. According to the Bonferroni t-test results, there was a significant difference between the press pressures of 12.5 kg cm^{-2} and the range 2.5/5/7.5 kg cm^{-2} in MOR values, between the press pressures of 12.5 kg cm^{-2} and 2.5 or 5 kg cm^{-2} in MOE values, and between the press pressure of 12.5 kg cm^{-2} and the range 2.5/5/7.5/10 kg cm^{-2} in CS values. No significant differences were found for thicker glue lines with the press pressure of 2.5 to 5 kg cm^{-2} in MOR and MOE values.

The mean TS and WA values were in the ranges of 2.61 to 6.92% and 50.95 to 67.88%, respectively. The press pressure affected TS and WA ratios. As the press pressure increased, the TS rates increased but WA rates decreased. An increase in TS values with increasing press pressures is explained by an increasing spring-back effect (Unsal *et al.* 2011) due to release of the compressive stresses (Wong *et al.* 1999). On the other hand, low WA values are explained as being a result of reduced porosity due to higher compaction rate because of increasing press pressures (Wong *et al.* 1999). Deeper glue penetrations in relation to higher press pressures may also have a contribution to lower WA rates. The ANOVA results showed that the press pressure of 12.5 kg cm^{-2} had the highest TS ratio and the lowest WA ratio. According to the Bonferroni t-test results, there was a significant difference between the press pressures of 12.5 kg cm^{-2} and the range 2.5/5/7.5/10 kg cm^{-2} in TS values and between the press pressures of 12.5 kg cm^{-2} and either 2.5 or 5 kg cm^{-2} in WA values. On the other hand, no significant difference was found between the press pressures of 7.5, 10, and 12.5 kg cm^{-2} with respect to WA values.

CONCLUSIONS

1. Laminated veneer lumber (LVL) pieces were successfully manufactured from half-round sliced veneers of *Populus x euramericana* (I-214) with the PF adhesive using press pressures ranging from 2.5 to 12.5 kg cm^{-2} in increments of 2.5 kg cm^{-2}. For thinner GLT, improved SG, WA, and mechanical properties, higher press pressures (7.5 kg cm^{-2} or more) can be recommended. The press pressure of 12.5 kg cm^{-2} had a drastic effect on all properties. The optimum press pressure was found to be 10 kg cm^{-2}. It may be risky to use the press pressures of above 10 kg cm^{-2} at this level of spreading rate and heat with the PF adhesive because of a possible joint starvation problem.
2. Relationships between GLT and mechanical properties (except CS) were stronger than that of SG and mechanical properties
3. GLT is one of the important indicators of degree of adhesive penetration to wood. It may be possible to use GLT to control the bond quality and strength of LVLs and other wood based wood composites. Further investigations are needed to use GLT for non-destructive prediction of mechanical properties.

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