Influence of Press Pressure on the Properties of Parallel Strand Lumber Glued with Urea Formaldehyde Adhesive

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The effects of press pressure on laboratory-made parallel strand lumbers (PSLs) that were manufactured from fast-growing rotary-peeled I-77/51 (*Populus deltoides*) hybrid poplar clones' veneer strands with a urea formaldehyde (UF) adhesive using press pressures ranging from 7.5 to 15 kg cm^{-2} in increments of 2.5 kg cm^{-2} were investigated. The physical and mechanical properties of PSL were affected by the press pressures. However, press pressures did not affect the combustion properties. Results indicated that higher press pressures lead to higher densification or compaction rates and specific gravities (SGs). For improved physical and mechanical properties, higher press pressures were found to be necessary. A press pressure of 12.5 kg cm^{-2} was found to be the optimum press pressure in relation to PSL properties. There are positive correlations among SG and mechanical properties as well as press pressures. The results may provide valuable information to assess the behavior of structural composite lumbers, including PSLs, that are manufactured using low and high press pressures. Utilization of fast-growing tree species is possible because their strength properties are improved through pressing.

Keywords: Parallel strand lumber (PSL); Urea formaldehyde (UF); Populus deltoides; Press pressure

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INTRODUCTION

The need for more effective use of wood materials and improved properties has led engineers to focus on the study of structural composite lumbers, including parallel strand lumbers (PSLs). PSLs are considered suitable alternatives to lumber and other lumber-like products. They are manufactured from veneer strands glued parallel to the longitudinal axis of the members (Kurt *et al.* 2012). The process of stranding reduces many of the timber's natural-growth and strength-reducing characteristics, such as knots, pitch pockets, and grain slope (Porteous and Kermani 2007), which have a strong influence on PSL properties. PSL uses approximately 64% of the volume of a log, as compared with the 52% for laminated veneer lumber (LVL) and 40% for solid sawn lumber (SL) (Fell 1999). The PSL manufacturing process can utilize waste material from a plywood or LVL operation because it is possible to use less than full-width veneer for PSL manufacturing (Stark *et al.* 2010).

PSL has advantages over sawn lumber not only in higher wood utilization rate but also in strength, predictability of performance, available sizes, dimensional stability, and treatability (Nelson 1997). Also, PSL is less prone to shrinking, warping, cupping, bowing, or splitting (Canadian Wood Council 1997). PSLs can be used for the same structural applications as traditional sawn lumber, such as girders, posts, beams, headers, joists, studs, lintels, and columns (Nelson 1997; Canadian Wood Council 1997).

Adhesive selection in PSL production depends on the exposure conditions, end use, manufacturing conditions, technology, dimensions, treatment order, and design requirements (Kurt 2010). For exterior exposure conditions, waterproof structural adhesives are used (typically phenol resorcinol formaldehyde) (Nelson 1997), and for interior exposure conditions, urea–formaldehyde (UF) adhesive can be used (Kurt and Çavuş 2011). The use of UF adhesives can be advantageous due to their water solubility, good adhesion, high curing rate, low cost (Peep *et al.* 2006), non-flammability, arc resistance, good thermal properties, and absence of color in the cured state (Raval *et al.* 2005). Urea–formaldehyde resins are probably the most widely used thermosetting resin for wood (Eckelman 1999).

The bond quality is one of the most critical factors in the performance of PSLs. It is affected by the amount of adhesive penetration into the wood substrate during manufacture of wood composites (PSLs) (Scheikl 2002). The press pressure is one of the main factors that influence the penetration of adhesives (Brady and Kamke 1988). The adhesives are forced to spread and penetrate into porous, fibrous materials and into the roughness of the surfaces by applied pressure (Cognard 2005). To achieve the required strength, the application of pressure is often required (Davis 1997). The press pressure is one of the important manufacturing processes that influence the complicated adhesive–wood interaction in the bonding process of strand products such as PSLs (Huang 2011).

The effect of press pressures on LVLs' selected properties has been studied thoroughly by Kurt and Çil (2012a; 2012b). On the other hand, research dealing directly with the effect of press pressures on properties of PSLs with different adhesives has been limited. The objective of this research was to determine the effect of press pressures (7.5, 10, 12.5, 15 kg cm^{-2}) on selected physical and mechanical properties of PSLs manufactured from rotary-peeled, I-77/51 veneer strands, glued with UF adhesives under laboratory conditions for semi- and non-structural applications. Press pressures below 7.5 kg cm^{-2} and above 15 kg cm^{-2} were not found suitable for PSLs manufacturing due either to their ineffectiveness in the bonding of veneer strands or due to a joint starvation problem, respectively. The optimum press pressure was determined in relation to tested properties. The relationships between the specific gravities (SGs) in relation to press pressures and properties of PSLs also were studied.

EXPERIMENTAL

Wood Veneers

Twelve-year-old I-77/51 (*Populus deltoides*) logs with diameters of 36 cm and lengths of 240 cm were harvested from the Adapazari region in Turkey. They were rotary-peeled into 3.0±0.1-mm-thick veneers without steaming due to their high moisture content and low density. They were dried to a moisture content of 6% to 8% at a plywood mill in Sakarya, Turkey. They were transferred to an engineered-wood-products laboratory and clipped to approximately 600 mm × 19 mm × 3 mm strands for manufacturing PSLs.

Adhesive

A commercial UF adhesive was used. This UF adhesive has a solids content of 65±1%, and 10% NH_4Cl was added as a hardener (Polisan 2012).

Fig. 1. Images of manufactured PSLs

PSL Manufacturing

To manufacture experimental eight-ply PSLs, adhesives were spread on strands using a double-roller glue-spreading machine on both sides, and they were immediately assembled with their tight sides facing out on each veneer with their grain directions parallel to each other. The adhesive spreading rate was 200 g m^{-2}; this was held constant for all press pressures. The gram weight pick up was calculated in accordance with ASTM D899 (2000). Billets were hot-pressed at a temperature of 110 °C for 30 min and at pressures of 7.5, 10, 12.5, and 15 kg cm^{-2}. After the pressing period, each PSL measured approximately 20 mm in thickness by 500 mm in width by 500 mm in length. They were further cut in accordance with specific test dimensions (Table 1) and conditioned to reach an equilibrium moisture content of 10±2% at a relative humidity of 65±1% and a temperature of 20±3 °C.

Table 1. Dimensions of Specimens for Specified Tests

Test	Dimensions (mm)
Oven-dry specific gravity (SG) Moisture content (MC)	Thickness × 20(w) × 30(l)
Thickness swelling (TS) Water absorption (WA)	Thickness × 100(w) × 100(l)
Modulus of rupture (MOR) Modulus of elasticity (MOE)	Thickness × 20(w) × 360(l)
Compression strength parallel to grain (CS)	Thickness × 20(w) × 30(l)
Combustion	19.5(t) × 9.5(w) × 1016(l)

Testing

The physical, mechanical, and combustion properties tested included moisture content (MC), SG, dimensional stability (thickness swelling (TS), and water absorption (WA) (24 h)), modulus of rupture (MOR), modulus of elasticity (MOE), and compression strength (CS) (parallel to grain) values of PSLs, and they were determined in accordance with TS 2471 (1976), TS 2472 (1976), TS 3639 (1988), TS 2474 (1976), TS2478 (1976), and TS 2595 (1977), respectively. Twenty replicates were tested to determine the mechanical properties and SG. Ten replicates were tested to determine the physical properties. The combustibility characteristics of PSLs were determined according to ASTM E69 (2002) procedure B. Five replicates were tested for each group, as required by the ASTM E69 (2002) standard. At the end of the testing, the weight loss (WL) percentages of specimens exposed to the flame were reported. The dimensions of specimens are given in Table 1. PSLs were tested flat-wise to failure in bending under center point loading to determine MOR and MOE. The span-to-depth ratio was fixed at 15 and adjusted for each specimen for 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).

To explain the strength increases of PSLs compared with solid wood (SW) properties in relation to the SG, a compaction factor (*CF*) was calculated according to Bao *et al*. (2001). The *CF* value is used to determine the degree of compaction or densification (Kurt and Çil 2012a). High *CF* ratios indicate higher densification. *CF* can be expressed as,

$$CF = D_L / D_S \tag{1}$$

where D_L is PSL's SG and D_S is SW's SG. SW's SG is reported to be 0.37 (Kurt 2010).

Statistical Analysis

Analysis of variance (ANOVA) was used to determine the effect of press pressure on selected physical, mechanical, and combustion properties of PSLs, using the SAS statistical package program (SAS 2001). The resulting F-value was compared with the tabular F-value at the 95% probability level. Statistical comparisons were made only between PSL specimens. Regression analyses were performed among MOE, MOR, CS, and SG, as well as between press pressure and SG, to determine their interrelationships.

RESULTS AND DISCUSSION

The average values and coefficient of variations (COV) of the SG, TS, WA, MOR, MOE, CS, and WL of PSLs are given in Table 2, along with the values of the respective press pressures. The COVs are usually within acceptable limits. The relatively low percentage values for COV indicated that variability of properties was low. The results show that increased press pressure caused significant improvement in the physical and mechanical properties. On the other hand, the combustion properties were not significantly ($p < 0.8238$) affected by press pressure. According to the statistical analysis results, the press pressure affected most of the PSLs' properties significantly. A Bonferroni *t*-test result is given for each property separately. MC values were found to be 10±2%.

The mean SG values of PSLs ranged from 0.40 to 0.46 (Table 2). A relationship was found between SGs and press pressures, with coefficients of determination (R^2) of 0.60. Also, very strong linear correlations were found between SG and MOR, MOE, and CS, with R^2 of 0.97, 0.99, and 0.81, respectively. Also, moderate to good relationships were found between press pressures and SG, TS, MOR, MOE with R^2 of 0.60, 0.73, 0.64 and 0.63, a very strong relationship between press pressures and CS with R^2 of 0.93. This demonstrates that most of the mechanical properties of PSLs were correlated with SG (Kamke 2006) as well as press pressures. The formation of SG is determined by the amount of and duration of press pressure (Pichelin and Dunky 2002) and other factors related to adhesives and wood. An increase in press pressure causes an increase in compression rate and contact in wood veneers (Mascia and Kramer 2009) and forces more liquids into the veneers (Palka 1964). The SG of PSLs that were manufactured using a press pressure of 12.5 kg cm^{-2} was higher than that of fir (*Abies alba*) (0.45), radiata pine (*Pinus radiata*) (0.45), and spruce (*Picea orientalis*) (0.47) woods (Bozkurt and Erdin 1997). According to the Bonferroni *t*-test results, SG values were significantly different ($p < 0.0001$) between a press pressure of 12.5 kg cm^{-2} and press pressures of 7.5, 10, and 15 kg cm^{-2}.

The *CF* values of PSLs fell within a wide range, between 1.08 and 1.24. The *CF* values increased with increasing press pressure. The increase in *CF* values can be attributed to the compression of wood due to press pressure (Kurt and Çil 2012a) and the presence of heat. Higher *CF* values provide more contact between strands and result in higher strength (Liu and Lee 2003) and SG. A press pressure of 12.5 kg cm^{-2} caused the largest degree of compaction. Thus, the critical press pressure would appear to be 12.5 kg cm^{-2}.

The mean TS and WA values were in the ranges of 7.16% to 19.79% and 80.48% to 90.44%, respectively. The percentage of TS increase ranged from a low of 68.44% to a high of 176.44% compared with that of the press pressure at 7.5 kg cm^{-2}. The TS increase is reported to be the result of a spring-back effect (Unsal *et al.* 2011) due to the release of compressive stresses (Wong *et al.* 1999). On the other hand, lower WA values were developed as a result of reduced porosity due to the higher compaction rate (Wong *et al.* 1999) and deeper glue penetration in relation to higher press pressure (Kurt and Çil 2012b). According to the Bonferroni *t*-test results, TS and WA values were significantly different ($p < 0.0001$) between a press pressure of 12.5 kg cm^{-2} and press pressures of 7.5, 10, and 15 kg cm^{-2}.

Table 2. Properties of the Tested PSL Specimens

Properties	Press Pressures (kg cm^{-2})			
	7.5	10	12.5	15
SG	0.40 **C** (5.00)	0.43 **B** (2.33)	0.46 **A** (4.35)	0.44 **B** (4.55)
CF	1.05	1.16	1.24	1.19
TS (%)	7.16 **D** (10.61)	12.06 **B** (12.19)	10.04 **C** (18.03)	19.79 **A** (10.46)
WA (%)	90.72 **A** (5.34)	85.90 **A** (3.73)	80.48 **B** (3.43)	90.44 **A** (5.13)
MOR (MPa)	38.26 **C** (18.50)	57.56 **B** (8.29)	68.02 **A** (4.60)	61.11 **B** (5.99)
MOE (MPa)	4448.47 **D** (9.37)	5839.02 **C** (8.17)	7073.33 **A** (4.30)	6298.13 **B** (6.80)
CS (MPa)	40.24 **C** (3.01)	45.44 **B** (3.76)	48.23 **A** (7.34)	49.41 **A** (4.82)
WL (%)	84.44 **A** (0.51)	84.51 **A** (0.46)	84.35 **A** (0.94)	84.97 **A** (2.40)

Bonferroni *t*-test groupings are given in bold capital letters. Means with the same letter are not significantly different. Coefficient of variations (%) are given in parentheses. SG, specific gravity; CF, compaction factor; TS, thickness swelling; WA, water absorption; MOR, modulus of rupture; MOE, modulus of elasticity; CS, compression strength parallel to grain; WL, weight loss after combustion test.

Mechanical properties increased as press pressures increased above the press pressure of 7.5 kg cm^{-2}, similar to all physical properties. The test results showed that MOR, MOE, and CS increased by 77.78%, 60.49%, and 19.86%, respectively, at a press pressure of 12.5 kg cm^{-2} compared with a press pressure of 7.5 kg cm^{-2}. The press pressure had the greatest effect on the MOR and MOE. The largest increases in MOR and MOE values were found in PSLs pressed at the 12.5-kg cm^{-2} press pressure. The results proved that PSLs' strength can be improved by increasing the amount of densification (Nelson 1997) using high press pressures (Kurt *et al.* 2012). Other reasons for improved mechanical properties are that higher press pressures will do the following: help to solve problems of voids and surface irregularities (Kurt *et al.* 2012), repair processing damage of the wood surface (Scheikl 2002), promote adhesive penetration (Frihart 2005), ensure veneer strands are evenly distributed and that the resin has thoroughly interlocked with the strands (Huang 2011), generate good bonding through greater interfacial contact between veneer strands (Chapman 2006), and allow better stress transfer between laminates (plies) (Scheikl 2002). Results of this study showed good agreement with Örs *et al.* (2001) and Kurt and Çil (2012a; 2012b), whose studies were related to the effect of press pressure on some mechanical properties of plywood and LVLs bonded with melamine urea formaldehyde and phenol formaldehyde adhesives, respectively. The ratios of mechanical properties' improvement were different due to different forms of materials and adhesives uses. According to the Bonferroni *t*-test results, there were significant differences in MOR and MOE values ($p < 0.0001$) between press pressures of 12.5 and press pressures in the range of 7.5/10/15 kg cm^{-2}, and between press pressures of 12.5 and press pressures in the range of 7.5/10 kg cm^{-2} in CS values.

The press pressure of 15 kg cm^{-2} resulted in a decrease in MOR and MOE and an increase in WA and TS properties. Press pressures above 15 kg cm^{-2} inevitably lead to joint starvation. Thus, it is not possible to form a glue line, and no bonding strength can be obtained (Dunky 2003). Also, excessively high pressure causes compression of the wood beyond its proportional limit (Marra 1980).

CONCLUSIONS

1. Parallel strand lumber specimens (PSLs) were successfully manufactured from rotary-peeled veneer strands of *Populus deltoides* (I-77/51) with a UF adhesive using press pressures ranging from 7.5 to 15 kg cm^{-2} in increments of 2.5 kg cm^{-2}.
2. For improved SG, WA, and mechanical properties, higher press pressures (7.5 kg cm^{-2} or more) can be recommended. On the other hand, the combustion properties were not affected by the press pressure.
3. The optimum press pressure was found to be 12.5 kg cm^{-2}. It may be risky to use pressures higher than 12.5 kg cm^{-2} or lower than 7.5 kg cm^{-2} at this level of spreading rate and heat with the UF adhesive because of possible bonding and joint starvation problems, respectively.
4. The press pressure may depend on wood species, the moisture content of wood, adhesive properties, other press parameters, factory conditions, and strength requirements.

5. Densification using higher press pressures can be identified as an important factor in the improvement of most of the physical and mechanical properties of wood.
6. Strong relationships between SG/press pressures and properties of PSLs were found. The findings may be used to predict the strength properties of PSLs.
7. The use of these findings may lead to more careful decision-making for manufacturing PSLs using fast-growing tree species with different press pressures.

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