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Research Article

Laminated veneer lumber (LVL) manufacturing using three hybrid poplar clones

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Abstract: Laminated veneer lumbers (LVLs) were manufactured from veneers of 3 rotary peeled fast growing hybrid poplar clones, I-214 (*Populus ×euramericana*), I-77/51 (*Populus deltoides*), and S.307-26 (*Populus deltoides*), with a phenol formaldehyde (PF) adhesive. Two *Populus deltoides* clones that are grown in Turkey were used for the first time in LVL production. The clone effect on selected LVLs' physical, mechanical, and combustion properties were investigated and compared to those of host woods (HWs). In addition, the suitability of 2 new *Populus deltoides* clones in addition to *Populus ×euramericana* was determined for LVL manufacturing. The properties of LVLs were affected by clone types. *Populus deltoides* clones had better physical, mechanical, and combustion properties compared to those of *Populus ×euramericana*. This could be attributed to the higher density and fiber length values of *Populus deltoides* clones. S.307-26 clone had the highest and I-214 had the lowest physical, mechanical, and combustion properties among 3 different hybrid poplar clones. Contribution factor, compaction factor or densification, improvement rate, manufacturing technique, and LVL technology were counted among the reasons for the higher LVLs' properties compared to those of HWs. The findings of the present research may be used to increase the use of fast growing poplar wood for value added products, i.e. LVLs by providing scientific data.

Key words: Hybrid clone, laminated veneer lumber, phenol formaldehyde, poplar, *Populus ×euramericana*, *Populus deltoides*

Üç hibrit kavak klonu kullanarak tabakalanmış kaplama kereste (TAK) üretimi

Özet: Tabakalanmış kaplama keresteler (TAK) üç farklı hızlı gelişen hibrid kavak klonları; I - 214 (*Populus ×euramericana)*, I-77/51 *(Populus deltoides)* ve S.307-26 (*Populus deltoides)* soyma kaplama levhalarından fenol formaldehit tutkalıyla üretilmiştir. Türkiye'de yetiştirilen iki *Populus deltoides* klonu ilk defa TAK üretimi için kullanılmıştır. Klon tipinin TAK'ların seçilmiş fiziksel, mekanik ve yanma özellikleri üzerine etkileri araştırılmış ve konuk (referans) masif ağaç malzeme özellikleriyle karşılaştırılmıştır. Ayrıca, *Populus ×euramericana* klonuna ek olarak, iki yeni hibrit *Populus deltoides* klonunun TAK üretimine uygunluğu belirlenmiştir. TAK'ların özellikleri klon türünden etkilenmektedir. *Populus deltoides* klonları *Populus ×euramericana*'ya göre daha iyi fiziksel, mekanik ve yanma özellikleri göstermiştir. Bu *Populus deltoides* klonlarının daha yüksek yoğunluk ve lif uzunluğu değerlerinden kaynaklanabilir. Üç farklı hibrit kavak klonu arasında, S.307-26 klonu en yüksek, I-214 klonu ise en düşük fiziksel, mekanik ve yanma özelliklerine sahiptir. TAK'ların özelliklerinin konuk masif ağaç malzemeye göre daha yüksek olmasının nedenleri arasında katkı

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faktörü, sıkılaştırma faktörü veya yoğunlaştırma, artış oranı, üretim tekniği ve TAK teknolojisi sayılabilir. Bu araştırma sonuçları, hızlı gelişen kavak odununun TAK gibi katma değerli ürünlerin kullanımını bilimsel veriler sunarak arttırmak için kullanılabilir.

Anahtar sözcükler: Fenol formaldehit, hibrit klon, kavak, *Populus ×euramericana*, *Populus deltoides***,** tabakalanmış kaplama kereste (TAK)

Introduction

Potential utilization of fast growing and lesser known species, i.e. poplar, as an environmentally friendly alternative source of raw material for pulp production (Kırcı and Akgül 2002) and wood-based composites for structural applications should be determined carefully. Increasing demands for wood-based structural materials with decreasing quality and quantity of raw materials are forcing the industry to utilize fast growing trees that have unfavorable properties (Bejo and Lang 2004). This is possible by using advanced manufacturing and bonding technologies. Laminated veneer lumber (LVL) may be one of the important solutions concerning raw material economy. LVL is one of the well-known and commercially produced engineered wood products (EWPs) in the forest products market in North America and Europe. LVLs can be used for structural and non-structural purposes due to their high strength, dimensional stability, consistency, and treatability (Nelson 1997).

In fact, LVLs are not a new development. Their production began in the 1940s during the Second World War and they have been commercially produced since the 1980s. LVLs can be defined as structural composite lumbers that are 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. LVLs have advantages over sawn wood since their wood utilization rates (52%) are higher than those of sawn woods (40%) (Nelson 1997). The wood material is one of the important factors in the production of LVLs. This factor includes species, quality, dimensions, mechanical, physical, and other properties, and the suitability for treatment and durability.

LVLs are commonly manufactured from Douglas fir and Southern pine (Nelson 1997), but now planned, new EWPs plants are available in hardwood producing areas to utilize underutilized species such as aspen, poplar and other soft hardwoods (The Woodland Steward 1995). Any tree species can be used as long as their physical and mechanical properties are acceptable for the LVL production including off-grade and fast growing species.

Utilization of fast growing species such as radiata pine (*Pinus radiata*) (Harding and Orange 1998), scots pine (*Pinus sylvestris* L.) (Çolak et al. 2004), eucalyptus (Wang et al. 1992; Gaunt et al. 2003; Aydın et al. 2004), and poplar (Shukla et al. 1996; Wu et al. 1998; Nimkar and Mohapatra 2002; Uysal and Kurt 2005; Burdurlu et al. 2007; Kurt and Mengeloğlu 2008; Keskin 2009) were reported in the manufacture of LVLs.

Many poplar species can be hybridized easily and propagated from cuttings for genetically improved growth and disease resistance (Bannoun et al. 1984). Hybrid woods may have superior growth, improved form, greater adaptability, and improved fiber characteristics (Balatinecz and Kretschman 2001). Hybrid poplar (*Populus*) species have been managed on farmlands commercially and provide a fast growing material source (Allig et al. 2000) to forest industries.

In Turkey, forest lands total 21.19 million ha, although less than half of this is real forest land; the annual increment of Turkey's forestland is about 36.28 million m^3. Although total consumption is 25.41 million m^3 (including timber from private resources, export, and illegal cutting) (State Planning Organization 2007), only 13.90 million m^3 round wood is harvested by the Forest Directorate. In addition to this production, close to 3.87 million m^3 poplar wood production is realized annually, of which 55% comes from hybrid poplar clones (Zoralioğlu 2003).

The Poplar and Fast Growing Forest Trees Institute of Turkey has been working on different hybrid poplar clones for industrial applications. In addition to the well known *Populus ×euramericana* (I-214) clone, 2 new hybrid poplar clones (*Populus deltoides*) (I-77/51 and S.307-26) have been selected for the present study due to promising results from a pilot study (Tunçtaner et al. 2004) that determined their growth performances and some technological wood properties. Using hybrid poplars for manufacturing LVLs is beneficial since they offer a solution to the main problem of the wood products industry to develop products using forest resources efficiently owing to the fact that the availability and quality of timber are becoming worse. With the introduction of LVLs and other EWPs, the utilization of hybrid poplar clones will increase (Kurt and Mengeloğlu 2002).

The main objective of the present research was to determine the suitability of 3 different hybrid poplar clones, I-214 (*Populus ×euramericana*), I-77/51 (*Populus deltoides*), and S.307-26 (*Populus deltoides*), for use in the manufacture of LVL with a phenol formaldehyde (PF) adhesive under laboratory conditions. It was also aimed to determine the clone effect on selected LVLs' physical, mechanical, and combustion properties. I-77/51 and S.307-26 clones were used for the first time for LVL production in Turkey. Their properties were compared with those of their host woods (HWs).

Materials and methods

Materials

Wood

A total of 15 trees from 3 different hybrid poplars, I-214, I-77/51, and S.307-26, were felled in poplar plantations in the Adapazarı region. The trees were cut into logs for veneer production by a rotary peeling method for LVL production or HWs for testing their selected properties. The LVLs used in this study were manufactured using rotary peeled veneers. Logs were not steamed or boiled prior to peeling. Rotary peeled veneers were dried to 6%-8% moisture content and clipped into 600 mm long by 600 mm wide by 3 mm thickness and shipped to a manufacturing site. The veneers were pre-selected for strength and appearance. They were conditioned in an environmentally controlled room in relative humidity of 65 ± 5% and a temperature of 20 ± 2 °C until they reached the equilibrium moisture content of 12%. Group numbers and their respective clone, clone number, and clone trade name are given in Table 1.

Adhesives

A commercial phenol formaldehyde adhesive (47 ± 1% solid) was used. Its specifications are given in Table 2 (Polisan 2010). The adhesive spreading rate was 200 g m^{-2}. The gram weight pick-up was calculated according to procedures described in ASTM D899 (2000).

Preparation of LVL

To manufacture 8-ply LVLs, adhesives were spread on the veneers [3 (t) mm by 600 (w) mm by 600 (l) mm] and they were immediately assembled with the tight side facing out on each veneer. Billets were hot pressed with their grain directions parallel to each other for 1 min mm^{-1} at a temperature of 140 °C and pressure of 1.2 MPa. After the pressing period, LVLs' final dimensions were reduced to 20 (t) mm by 500 (w) mm by 500 (l) mm using a circular saw. In addition, HW specimens were prepared from dried lumber to determine their physical, mechanical, and combustion properties and compared with those of LVLs. LVL and HW specimens (except combustion

Table 1. Specification of group, clone, clone number and clone trade name.

Group	Clone	Clone number	Clone trade name
P1	*Populus ×euramericana*	I-214	Canada
P2	*Populus deltoides*	I-77/51	Samsun
P3	*Populus deltoides*	S.307-26	İzmit

Table 2. Specifications of the phenol formaldehyde adhesive (Polisan 2010).

Properties	Value
pH at 20 °C	11.50
Viscosity at 20 °C	400 cps
Density at 20 °C, g cm^{-3}	1.21
Phenol formaldehyde, %	47 ± 1
Appearance	Red

specimens) were conditioned to an equilibrium moisture content of 12%.

Testing

Oven dry density (OD) and moisture content (MC) of LVLs and HWs were determined in accordance with TS 2472 (1976a) and TS 2471 (1976b), respectively, using specimens measuring approximately 20 (t) mm by 30 (w) mm by 30 (l) mm. Ten replicates for LVL and at least 30 replicates for HWs were used for OD and MC determinations.

Glue bond quality was determined by performing glueline shear strength tests according to procedures described in EN314-1 (1999); specimens were modified as in the European Laminated Veneer Engineering (ELVE) final report (Anonymous 1997). The forms and dimensions of specimens are shown in Figure 1. The bond quality was determined for 2 of the 7 gluelines; these being between the 3/4 and 4/5 layers. Ten replicates for LVL were used for testing glue bond quality.

Modulus of rupture (MOR) (perpendicular to grain) and modulus of elasticity (MOE) values were determined according to procedures described in TS 2474 (1976c) and TS 2478 (1976d), respectively. HWs and LVLs test specimens' dimensions were 20 (t) mm by 20 (w) mm by 360 (l) mm. The specimens were tested for bending using a Zwick Roell (Z010) testing machine. After completion of each test, a wood sample was cut from an undamaged section near the failure zone of each specimen for the MC and OD determinations. Ten replicates for LVL and 30 replicates for HWs were used to determine MOR and MOE.

To explain the strength increases (MOR and MOE) of LVLs compared to those of HWs, a

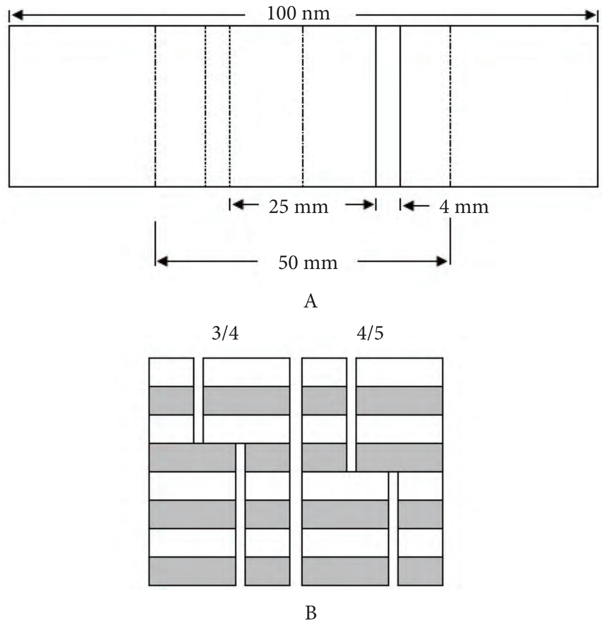

Figure 1. Glue bond quality specimens' forms (A) and dimensions (B).

compaction factor (*CF*) and an improvement rate (*I*) were calculated according to Bao et al. (2001).

CF can be expressed as

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

where D_L is LVL's OD and D_S is HW's OD. High *CF* ratios indicate higher densification.

I can be expressed as

$$I(\%) = \frac{P_L - P_S}{P_S} \times 100 \tag{2}$$

where P_L is LVL's strength and P_S is HW's strength. High *I* values indicate high increase in strength properties of LVLs compared to HWs.

According to Bao et al. (2001), large strength increases may originate from HWs' properties and only a small portion from processing variables (e.g., adhesive and hot panel assembly). To measure the effect of wood properties on LVLs' strength, contribution factor (C_f) was used. For the calculation of C_f guidelines set by Bao et al. (2001) were followed. C_f can be expressed as

$$C_f(\%) = (P_S / P_L) \times 100 \quad (3)$$

where P_S is HW's strength and P_L is LVL's strength. High C_f values indicate a large effect of HWs' properties on LVL and low C_f values indicate low effect of HWs' properties (manufacturing and other factors may have additional effects). It was aimed to identify the most probable cause of LVLs' performance compared to that of HWs. MOR and MOE values were used for the analysis since the bending strength is considered most important to LVLs' structural performance (Bao et al. 2001).

The compression strength (parallel to grain) (CS) values were determined according to procedures described in TS 2595 (1977). The test specimens' dimensions were 20 (t) mm by 20 (w) mm by 30 (l) mm. They were tested to failure using the Zwick Roell (Z010) testing machine. Ten replicates for LVLs and 30 replicates for HWs were used to determine CS.

Combustible properties of LVLs and HWs were determined according to ASTM E69 (2002) procedure B. Specimens (19.5 (t) mm by 9.5 (w) mm by 1016 (l) mm) were cut for the combustion testing. They were conditioned in an environmentally controlled room in relative humidity of 55 ± 5% and temperature of 20 ± 2 °C for 2 weeks. Five replicates were tested for each group as required by the standard. At the end of the testing, weight loss (WL) percentage of specimens exposed to the flame was reported.

Statistical analysis

Analysis of variance (ANOVA) was used to determine the clone effect on selected physical, mechanical, and combustion properties of LVLs using the SAS statistical package. The resulting F value was compared to the tabular F value at the 95% probability level. When there was a significant difference as a result of F tests, comparisons between means were made by Bonferroni t-test. Statistical comparisons were made only between LVL specimens. HWs' values were used for comparison.

Results

The mean OD values of LVLs and HWs fell within a narrow range, i.e. 0.43-0.49 (Table 3) and 0.32-0.38 g cm^{-3} (Table 4), respectively. LVLs manufactured

Table 3. Mean OD, MOR, MOE, CS, and WL of LVLs.

Properties	P1-LVL	P2-LVL	P3-LVL
OD (g cm^{-3})	0.43 (4.65) b	0.47 (4.26) a	0.49 (4.08) a
MOR (MPa)	77.64 (16.28) b	92.01 (18.18) a	95.82 (5.48) a
MOE (MPa)	6773.78 (6.34) b	7933.23 (4.96) a	8363.78 (5.16) a
CS (MPa)	46.45 (8.78) b	57.32 (1.76) a	57.98 (1.31) a
WL (%)	88.75 (2.03) a	83.24 (0.71) b	85.24 (0.47) b

Letters showing Bonferroni t-test (Bon) means with the same letter in a row are not significantly different. Coefficients of variations are given in parentheses.

Table 4. Mean OD, MOR, MOE, CS, and WL of HWs.

Properties	P1-HW	P2-HW	P3-HW
OD (g cm^{-3})	0.32 (12.50)	0.37 (2.70)	0.38 (10.53)
MOR (MPa)	48.54 (20.17)	59.77 (15.11)	61.04 (9.39)
MOE (MPa)	4777.82 (24.59)	5442.60 (13.41)	6065.48 (9.20)
CS (MPa)	35.11 (15.38)	31.07 (6.63)	36.31 (4.13)
WL (%)	95.51 (1.36)	95.24 (1.10)	94.89 (1.04)

Coefficients of variations are given in parentheses. Values were adopted from Kurt (2010).

from P3 had the highest OD values. The OD of LVLs was higher than that of HWs due to the effects of high pressure during the manufacturing process. According to Bonferroni t-test results, there was a significant difference between OD of groups P1-LVL and P2-LVL/P3-LVL (Table 3). On the other hand, there was no significant difference between OD of groups P2-LVL and P3-LVL (Table 3), both P2 and P3 being *Populus deltoides* clones. MC values of LVLs and HWs were found to be 10 ± 2%.

Mean glueline shear strength values between 3/4 and 4/5 layers including their coefficient of variations (COVs) are given in Table 5. MOR, MOE, CS, and WL values of LVLs and HWs and also their COVs are given in Tables 3 and 4, respectively. The ANOVA ($\alpha = 0.05$) results ($P < 0.0001$) indicated that differences in mean physical, mechanical, and combustion properties values were observed when different clone types were used. The Bonferroni t-test result was given for each property separately.

Mean glueline shear strength between 3/4 and 4/5 layers of LVLs fall within a wide range between 4.28 and 8.01 MPa (Table 5). P2 and P3 clones had similar glueline shear strength values. Small differences between the 2 different glue lines showed that the adhesive provided a good bond through different layers of the LVLs. The Bonferroni t-test result showed that there was a significant difference between clone P1-LVL and P2-LVL/P3-LVL (Table 5).

MOR values of LVLs and HWs were 77.64-95.82 and 48.54-61.04 MPa, respectively (Tables 3 and 4). All of the samples failed near the mid-span in tension zones. LVLs made of P1 had the lowest and P3 had the highest MOR values. The MOR values of LVLs were higher than those of their respected HWs. MOE values of LVLs and HWs were_6773.78-8363.78 and 4777.82-6065.48 MPa, respectively (Tables 3 and 4). Similar trends were seen for MOE results; MOE of LVLs' were higher than that of HWs' and P3 clone had the highest MOE values for LVLs and HWs. In the case of CS, values of LVLs and HWs ranged from 46.45-57.98 and 31.07-36.31 MPa, respectively (Tables 3 and 4). All CS specimens showed fiber crushing failure. Similar to MOR and MOE results, LVLs made of P1 clone had the lowest and P3 had the highest CS values. The CS values of LVLs were higher than those of HWs. The Bonferroni t-test results showed that there was a significant difference between P1-LVL and P2-LVL/P3-LVL. On the other hand, there was no significant difference between P2-LVL and P3-LVL.

Table 5. Mean glueline shear strength values (MPa) between 3/4 and 4/5 gluelines.

Clone group	Gluelines	
	3/4	4/5
P1	4.28 (20.09) b	4.53 (12.58) b
P2	7.90 (10.38) a	7.03 (7.82) a
P3	8.01 (10.49) a	7.34 (10.90) a

Letters showing Bonferroni t-test (Bon) means with the same letter in a column are not significantly different. Coefficients of variations are given in parentheses.

The mean WL values of LVLs and HWs were 83.24%-88.75% and 94.89%-95.51%, respectively (Tables 3 and 4). In HWs, P2 showed the lowest WL rate while P1 displayed the highest WL rate. In LVLs, P3 showed the lowest WL rate. The WL rate decreased between 7.08% and 10.17% compared to that of HWs. There was a significant difference between WL rate, similar to physical and mechanical properties as given above.

Discussion

The OD of LVLs was higher than that of HWs up to 34.38%. Approximately 165 g of cured PF adhesive was used to manufacture LVLs. High density of the PF adhesive (1.21 g cm^{-3}) might also contribute to that situation (Shukla and Kamdem 2009) in addition to densification. The results were in agreement with previous studies related to LVL from fast growing species reported in the introduction section. The OD of LVLs was higher than that of spruce (*Picea orientalis*) and fir (*Abies alba*) solid wood with 0.41 g cm^3 (Bozkurt and Erdin 1997).

Glue bond quality of LVLs bonded with PF adhesive was determined by this test. According to the glueline shear tests results, the adhesive provided good bond through the thickness of LVL. The results also proved that the adhesives sufficiently cured in the cores of the LVL since there were no differences between 3/4 and 4/5 glue lines shear strength values. All glueline shear strength values were comparable to that of LVL made from high quality birch veneers with a phenol based adhesive (Anonymous 1997). Two *Populus deltoides* clones (P2 and P3) performed similarly. Strong relationships were found between the OD and glueline shear strength values (R^2 = 0.88). Thus high density veneers produced high strength. Similar results were found in the ELVE (European Laminated Veneer Engineering) final report (Anonymous 1997).

The main advantage of LVLs was that their strength properties were better than those of their respective HWs. High *CF* and *I* values can be used to provide a meaningful explanation for the strength increase of LVLs. *CF* was up to 1.34 (Table 6). *I* of MOR and MOE was up to 59.95% and 45.76% (Table 6).

C_f was used to determine the effect of HWs' properties on LVLs' strength. In MOR, the C_f was the highest in P2 and the lowest in P1. In MOE, C_f was the highest in P3 and the lowest in P2 (Table 6). A comparison of the MOR and MOE among the 3 different poplar clones showed a relationship that higher MOR/MOE values of HWs corresponded to high C_f and were associated with higher LVLs MOR and MOE values, but P1 did not show this trend. The results showed that C_f cannot be used alone to explain the strength increase. The contributory effect of the adhesive use and manufacturing technique also play an important role in the strength increase (Bao et al. 2001). In LVLs production, strength can be increased by layering veneer strands by grade (Nelson 1997). Moreover, during LVLs' manufacturing, strength reducing can be eliminated; thus, they can be considered as better alternative to solid sawn lumber for different structural applications (Liu and Lee 2003). It is possible to control LVLs' manufacturing processes (such as drying, gluing, and pressing). This will give great control to the manufacturer to reduce manufacturing and strength variations.

Furthermore, according to de Boever et al. (2007), fiber length will probably affect the maximum load capacity (i.e. MOR). The fiber length of P1, P2, and P3 was 0.82, 0.87, and 0.87 mm, respectively (Kurt 2010). Longer fiber length of P2 and P3 may be used to explain higher LVLs' and HWs' MOR values compared to that of P1.

The MOR and CS of LVLs were higher than those of 2 commonly used species for LVL manufacturing: fir (*Abies alba*) and spruce (*Picea abies*) (Bozkurt and Erdin 1997). MOR, MOE, and CS values were comparable to commercial LVL design values published by the Canadian Construction Materials Centre (CCMC) (2006).

The mean WL rate after the combustion test for LVLs and HWs was 85.74% and 95.21%, respectively. Mean WL values of LVLs were considerably less than those of HWs. This can also be explained by effects of densification and manufacturing factors similar to those in the mechanical properties' increase.

The main aims of the present study were achieved by producing LVLs from 2 new fast growing hybrid *Populus deltoides* clones in addition to *Populus ×euramericana* (I-214) clone and improving their properties over HWs. The utilization of hybrid poplar clones could be expanded by using them for LVLs. The following results were found.

LVLs were successfully manufactured from rotary peeled hybrid I-214, I-77/51, and S.307-26 poplar

Table 6. Compaction ratio (*CF*), contribution factors (C_f), and improvement rate (*I*) of HWs vs LVLs (MOR and MOE).

HWs vs. LVL	*CF*	MOR		MOE	
		C_f(%)	*I* (%)	C_f(%)	*I* (%)
HWP1 vs. LVLP1	1.34	62.52	59.95	70.53	41.78
HWP2 vs. LVLP2	1.27	64.96	53.94	68.61	45.76
HWP3 vs. LVLP3	1.29	63.70	56.98	72.52	37.89

clone veneers with the PF adhesive. The results showed that physical, mechanical, and combustion properties of LVLs were improved compared to those of HWs. The physical, mechanical, and combustion properties of LVLs' were affected by clone types. LVLs made of S.307-26 had the highest and of I-214 had the lowest OD, MOR, MOE, CS, and WL values among the 3 different hybrid poplar clones. LVLs' mechanical properties were higher than those of HWs. Properties' improvements of LVLs depended on contribution factor, compaction factor or densification, improvement rate, manufacturing technique, and LVLs technology. Strength properties values of LVLs were comparable to those of commonly used softwoods [i.e., poplar (*Populus nigra*), fir, spruce].

Two *Populus deltoides* clones, I-77/51 and S.307-26, performed similarly. They may be more suitable for structural composite lumber (i.e. LVL) manufacturing than I-214. This can be explained by higher density and fiber length of *Populus deltoides* clones.

Utilization of fast growing hybrid poplar clones for manufacturing LVLs and other value added wood-based composites is beneficial to the forest products and building industries since poplar wood will provide a relatively inexpensive and sustainable source of material. This will solve a raw material problem of the forest-based industries by providing relatively affordable wood materials.

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