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EVALUATION OF THE MECHANICAL PROPERTIES OF POPLAR LAMINATED VENEER LUMBER (LVL) REINFORCED WITH OAK, BEECH, AND EUCALYPTUS VENEERS

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ABSTRACT

Structural composite lumber is produced from various tree species, and numerous laboratory studies have examined its mechanical properties. In this study, LVL boards were produced using poplar, oak, beech, and eucalyptus veneers in the outer layers and poplar veneers in the middle layers. Melamine-urea-formaldehyde adhesive was used in the production of the boards. The modulus of rupture, modulus of elasticity, splitting strength, compression strength perpendicular to the grain, hardness, and screw holding capacity of the produced boards were determined. According to the obtained data, test specimens with oak, beech, and eucalyptus as outer layers had higher mechanical properties than the control group. Furthermore, the modulus of rupture and modulus of elasticity of LVL boards with oak on the top and bottom surfaces were 50% and 99% greater than those of the control group, respectively. However, no significant increase in splitting strength was found.

Keywords: LVL; Poplar veneer; Reinforcement; SCL.

INTRODUCTION

Solid wood and wood-based materials are widely used in wooden structures. These materials are classified in various ways. Based on its technological composition, structural wood is divided into solid wood, modified wood, and wood composites, including laminated structural wood, veneer-based structural wood, agglomerated structural wood, and combined structural wood (Vaňová and Štefko 2021). Structural composite lumber holds a special place in these classifications. Structural composite lumber consists of four different materials: Laminated Veneer Lumber (LVL), Parallel Strand Lumber (PSL), Oriented Strand Lumber (OSL), and Laminated Strand Lumber (LSL). Today, LVL is the most widely produced and used structural composite lumber. LSL, on the other hand, makes the most efficient use of raw wood materials. These types of lumber are used in structural applications as girders, beams, headers, joists, studs, and columns (Nelson, 1997). LVL is produced under various trade names, such as Micro-Lam, Versa-Lam, and Kerto-LVL. It is primarily used in the construction of wooden houses, wooden commercial buildings, and other wooden structures. LVL has been used as a load-bearing structural composite lumber in wooden structures. However, it is now also being used as a load-bearing panel in wooden structures. For example, the Kerto® LVL Q-panel is produced for this purpose (URL 1, 2025).

Numerous scientific studies have examined the physical and mechanical properties of LVL. For example, Bao *et al*. (2001) investigated some of the mechanical properties of LVL produced from three different poplar clones and also compared LVL with solid wood by calculating the contribution factor. Çolak *et al*. (2007) investigated the effects of the steaming, aging, and drying conditions on the mechanical properties and durability of LVL and solid lumber from beech and spruce. Erdil *et al*. (2009) compared the mechanical properties of solid wood and laminated veneer lumber produced from Turkish beech, Scots pine, and Lombardy poplar. The adhesive type and wood species had significant effects on the mechanical properties of the LVL specimens. Kurt *et al*. (2011) investigated the impact of the pressure duration on some selected properties of LVL. Kurt and Çil (2012) determined the effects of the press pressure on the glue line thickness and some selected properties of LVL. Bal and Bektaş (2012) investigated the impact of hot-setting adhesives on the bending properties of LVL. Hashim *et al*. (2011) investigated the effects of cold-setting adhesives on the properties of LVL produced from oil palm wood and rubber wood. In addition, De Melo *et al*. (2015), Bal and Bektaş (2012), and Altınok (2019) investigated the effects of adhesive type on selected properties of LVL. De Melo *et al*. (2014) investigated the impact of veneer thickness on the physical and mechanical properties of LVL.

In addition to studies investigating the effects of factors such as wood type, glue type, press pressure, and press time on selected properties of LVL (some of which were listed above), studies on LVL reinforcement have also been conducted. For example, Larson *et al*. (1987) investigated the effect of butt joint reinforcement in parallel-laminated veneer lumber (LVL). Wei *et al*. (2013) investigated the mechanical properties of poplar LVL reinforced with carbon fiber. Bal (2014) produced poplar LVL reinforced with glass fiber fabric and investigated its mechanical properties. Wang *et al*. (2015) made three types of reinforced LVL, including a carbon fiber-reinforced polymer (CFRP) sheet, glass fiber-reinforced polymer (GFRP) mesh, and a composite of the CFRP sheet and GFRP mesh, and evaluated the mechanical properties of the LVL. Bal (2021) reported some of the mechanical properties of LVL strengthened with a glass fiber net. Perçin (2023) investigated the compression strength parallel to the grains of heat-treated LVL reinforced with carbon fiber. Opazo-Vega *et al*. (2025) investigated the elastic properties of LVL panels produced from pine veneers reinforced with carbon and basalt fibers. In other studies, researchers investigated the reinforcement effect of using wood veneers with higher mechanical performances. For example, Wong *et al*. (1996) investigated the properties of rubber wood LVL reinforced with acacia veneers. H'ng *et al*. (2010) investigated some selected mechanical properties of LVL panels made from low-density wood species reinforced with Keruing veneers. Sulastiningsih *et al*. (2020) investigated some of the mechanical properties of oil-palm wood-based LVL reinforced with jabon and mahoni wood veneers.

A review of the previous studies cited above demonstrates that the effects of factors such as the wood species, veneer thickness, layer composition, adhesive type, press pressure, and press time on the mechanical properties of LVL have been extensively investigated. Furthermore, numerous studies have been conducted on reinforcing LVL with glass, carbon, and natural fibers. However, the reinforcement of low-performance wood species with veneer sheets derived from high-performance wood species has not been sufficiently investigated. Therefore, the aim of this study was to investigate the mechanical properties of poplar LVL faced with oak, beech, and eucalyptus veneers.

MATERIALS AND METHODS

Material

In the study, 3 mm-thick veneers were obtained from the following tree species: poplar (Populus spp.), oak (*Quercus petraea*), beech (*Fagus orientalis*), and eucalyptus (*Eucalyptus* *grandis*). These veneers were obtained using the rotary-cut method. The prepared veneer boards were 30 × 30 cm, and 6 veneers were used for each board. The average density of the poplar, oak, beech, and eucalyptus veneers was 388 kg/m^3, 615 kg/m^3, 589 kg/m^3, and 572 kg/m^3, respectively. Flawless veneers without cracks, knots, and rot were selected. In this study, one control group (with poplar veneer in all layers) and three experimental groups (with surface layers of oak, beech and eucalyptus veneers) were created, as shown in Fig. 1.

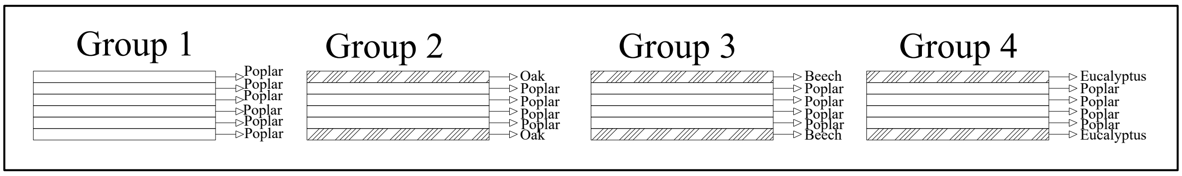

Fig. 1 LVL groups and veneer lay-up schemes.

MUF resin was used as the adhesive in this study. The adhesive was supplied by Polisan A.Ş. The adhesive had a solid percentage of 55±1%, viscosity (Cps at 20°C) of 150–350, pH of 9.0–9.2, density (at 20°C) of 1.230 kg/m^3, and jel time of 25-35 s (at 100°C). The adhesive was applied to the veneer surfaces without using any additives or fillers.

Production of LVL panels

To produce LVL boards, the loose surfaces of the veneer boards were first identified, and adhesive was applied with a brush. After gluing the veneer boards, the loose surfaces were positioned toward the center of the board. Almost 200 ± 10 g/m^2 of adhesive was used on the veneer surfaces. After gluing, the boards were placed in a hot press and a pressure of 5.5 kg/cm^2 was applied at 120°C for 18 min. Five LVL boards were produced for each group. The boards removed from the press were left to stand for one week, stacked, and then test samples were prepared.

Method

The bending test, splitting strength, compressive strength perpendicular to the grain, Janka hardness, screw holding capacity, and tensile shear strength (TSS) of the LVL test specimens were determined according to standards TS 2474, TS 7613, TS 2473, TS 2479, TS EN 13446, and TS EN 314-1, respectively. Bending test specimens were prepared with a board thickness of 1.5 cm, a width of 2 cm, and a length of 30 cm. Three test specimens were prepared from each board for each test, for a total of 15. Bending tests were conducted on a 10 kN capacity universal testing machine (UTM), as shown in Fig. 2. During the bending test, a force was applied to the side surface in an edgewise position. The test speed was 5 mm/min, the distance between the supports was 24 cm, the preload was 10 N, and the endpoint was 75% of the maximum force. In the splitting strength test, a 50 × 70 mm test specimen was prepared. A 32 mm diameter hole was drilled on one short side, and a tensile force was applied through this hole. A 20 × 20 × 15 cm (length × width × thickness) specimen was prepared to test the compressive strength perpendicular to the grain. The test was terminated when a fracture occurred in the test specimen or when the load decreased to 75% of the maximum force. A Janka test was performed to determine the static hardness. The penetration depth of the test head into the test specimen was set at 2.82 mm. To determine the screw holding capacity, test specimens were prepared with a square cross-section of 50 × 50 mm and a thickness equal to the board thickness. Zinc screws measuring 4 × 50 mm were used in the tests. The screws were screwed into the surface at the midpoint of the test specimen.

During the screw holding capacity tests, the preload was 10 N, the test speed was 5 mm/min, and the test endpoint was set at 75% of the maximum force. For the TSS tests, 12 test samples were prepared for each glue line (second, third, and fourth), totaling 72. The TSS tests were conducted on 15 air-dried samples and 15 samples treated with cold water. The treatment with cold water lasted 24 hours. During this time, the test samples were submerged in cold water. The samples were tested immediately after the treatment process was completed.

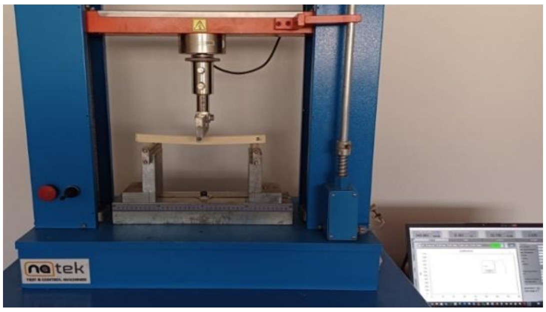

Fig. 2 Bending test and image of the test machine.

Statistical calculations

The data were organized in Excel and analyzed using a one-way ANOVA in SPSS to determine whether there were differences among the groups. The Duncan test was used to determine whether any groups differed significantly from each other in the statistically significant data.

RESULTS AND DISCUSSION

The air-dried densities of the LVL boards were calculated and are presented in Table 1. As shown, the average air-dried density values for the groups ranged from 417 to 511 kg/m3. The lowest density was measured in Group 1 (417 kg/m^3), with the highest measured in Group 2 (537.9 kg/m^3). An ANOVA test was performed to determine whether there was a statistically significant difference between the air-dried density values of the groups. The difference between the groups was statistically significant ($P < 0.001$). When the density values given in Table 1 were compared with the mechanical properties shown in the following tables, it could be seen that the LVL groups with higher densities (Groups 2 and 3) exhibited higher mechanical properties. Previous studies reported that LVL density affects its mechanical properties, and that higher mechanical properties are obtained from LVL with higher density (Erdil 2009; Bal 2012). However, this is not true for every mechanical property. In addition to density, the fiber structure, wood type (mature vs. young), the degree of fibrousness, and the distribution of wood cells can also affect the properties. It is particularly evident in the splitting strength test results.

Tab. 1 Density test data, ANOVA P value, and Duncan test results.

		Group 1	Group 2	Group 3	Group 4	P value
Density (kg/m^3)	x̄	417.6 **A***	537.9 **C**	522.6B **C**	511.1 **B**	0.000
	sd	29.2	20.5	40.7	19.3	-

x̄: arithmetic mean, sd: standard deviation, *: lowest value, with different letters (*A, B, C) indicating significant differences in Duncan test results.

The findings of the bending tests (Modulus of Rupture and Modulus of Elasticity) are given in Table 2. As shown, the modulus of rupture values for the test specimens ranged from 63 to 97 N/mm^2. The difference between the groups was statistically significant ($P < 0.001$). The highest bending strength values were measured in Groups 2 and 3, with the smallest measured in Group 1. Compared with the control group, the increases in bending strength for Groups 2 and 3 were approximately 50%. Similar results were obtained for the modulus of elasticity. The smallest modulus of elasticity was 5310 N/mm^2 in Group 1, and the highest was 10595 N/mm^2 in Group 2. The difference between the groups was statistically significant ($P < 0.001$). Compared with the control group, the experimental groups showed approximately 97–99% increases in modulus of elasticity. The ratio of the oak, beech, or eucalyptus veneer to the poplar veneer used in the experimental groups was one-third. Of the six veneer panels, four were made of poplar and two of other wood species. Despite this, the bending performance of the experimental groups was statistically significantly better than that of the control group. Similar results have been obtained in previous studies on this subject. For example, Wong *et al*. (1996) investigated the properties of rubberwood-based LVL reinforced with Mangium veneers. They reported that the bending properties of 5-ply rubberwood LVL reinforced with Mangium were significantly greater than those of unreinforced LVL, while those of 3-ply LVL were not. The MOR value for the 5-ply with reinforcement was 13% higher than that without reinforcement. Sulastiningsih *et al*. (2020) investigated some of the mechanical properties of oil-palm wood veneer-based LVL reinforced with jabon and mahoni wood veneers, and reported favorable results. In addition, H'ng *et al*. (2010) investigated the effects of incorporating Keruing veneers into LVL panels made from low-density wood species such as Pulai, Sesendok, and Kekabu Hutan. They reported that the presence of Kruing veneers as surface layers significantly increased the bending strength of the LVL panels. In previous studies on reinforcing LVL boards with glass or carbon fiber, the increase in flexural properties with reinforcement remained below 50% (Larson *et al*., 1987; Wei *et al*., 2013; Bal 2014; Bal et al., 2015; Wang *et al*., 2015; Sokolović, 2023; Opazo-Vega *et al*., 2025). In this case, reinforcing LVL sheets produced with veneer sheets with lower mechanical performance with veneer sheets with higher mechanical performance yielded better results than reinforcing them with synthetic fibers.

Tab. 2 Bending test data, ANOVA P value, and Duncan test results.

		Group 1	Group 2	Group 3	Group 4	P value
Modulus of Rupture (N/mm^2)	x̄	63.6 **A***	97.4 **C**	97.4 **C**	87.3 **B**	0.000
	sd	4.8	7.2	12.3	10.7	-
Modulus of Elasticity (N/mm^2)	x̄	5310.9 **A**	10595.0 **B**	10117.9 **B**	10498.9 **B**	0.000
	sd	358.9	449.3	1003.0	1171.9	-

x̄: arithmetic mean, sd: standard deviation, *: lowest value, with different letters (*A, B, C) indicating significant differences in Duncan test results.

The compression strength perpendicular to the grain test data, ANOVA P-values, and Duncan test results are presented in Table 3. As seen, the lowest compressive strength was measured in Group 1, and the highest was found in Group 3. The differences between the groups were statistically significant ($P < 0.001$). The higher compressive strength in Group 3 was due to the more homogeneous fiber structure of beech veneers compared to oak and eucalyptus veneers. Wood fibers are distributed homogeneously both along the length of the tree and from the pith to the bark. However, the greater presence of core rays in oak veneers affects the compressive strength. LVL material is used for structural members such as girders, beams, headers, and joists, where the load acts perpendicular to the fibers. Therefore, LVL material must have a high perpendicular-to-grain compression strength. In experimental groups, the use of oak, beech, and eucalyptus veneers on the top and bottom surfaces increased the compressive strength. However, this increase was not as significant as the increases in the flexural strength and modulus of elasticity in Groups 2 and 4. Only Group 3 achieved a 48% increase. However, even this increase was better than the increases in compressive strength obtained in reinforcement studies using glass or carbon fiber (Perçin, 2023; Perçin, 2025).

Tab. 3 Compression strength test data, ANOVA P value, and Duncan test results.

		Group 1	Group 2	Group 3	Group 4	P value
Compression strength (N/mm^2)	$\bar{x}$	9.0 **A**	11.1 **B**	13.3 **C**	11.0 **B**	0.000
	sd	1.6	1.2	2.0	1.5	-

$\bar{x}$: arithmetic mean, sd: standard deviation, *: lowest value, with different letters (*A, B, C) indicating significant differences in Duncan test results.

The screw holding capacity test data, ANOVA P values, and Duncan test results are given in Table 4. As seen in the table, the screw holding capacities of the control and experimental groups were statistically significantly different ($P < 0.001$). According to the Duncan test results, there was no difference between the experimental groups. The effects of the veneer types used in the experimental group on screw holding capacity were the same. The increase in screw holding capacity of the experimental groups compared to the control group was approximately 43%. This result was quite striking. In a reinforcement study using glass fiber (Bal, 2021), no such increase was reported, even in the experimental group in which glass fiber was used in all adhesive layers. Glass fiber reinforcement had a small effect on the screw-holding capacity of LVL panels. However, the impact of strengthening using stronger veneer sheets on the top and bottom surfaces, as in the presented study, is greater.

Tab. 4 Screw holding capacity test data, ANOVA P value, and Duncan test results.

		Group 1	Group 2	Group 3	Group 4	P value
Screw holding capacity (N/mm^2)	$\bar{x}$	23.5 **A**	32.8 **B**	34.5 **B**	32.6 **B**	0.000
	sd	1.9	4.2	5.5	2.6	-

$\bar{x}$: arithmetic mean, sd: standard deviation, *: lowest value, with different letters (*A, B, C) indicating significant differences in Duncan test results.

The splitting strength test data, ANOVA P-values, and Duncan test results are presented in Table 5. As shown, the lowest splitting strength (0.52 N/mm^2) was observed in Groups 1 and 2, and the highest splitting resistance was observed in Group 3. In fact, the other mechanical performances for the oak veneer used in Group 2 were quite high. However, its splitting resistance was low. This was due to the high number of core rays in oak wood, as shown in Fig. 3. These core rays extend from the pith to the bark, facilitating radial splitting of the wood. It is particularly problematic in veneer boards. For this reason, while the contributions of the oak veneer to the other mechanical properties of LVL boards were quite high, its effect on the splitting resistance was insufficient.

Tab. 5 Splitting strength test data, ANOVA P value, and Duncan test results.

		Group 1	Group 2	Group 3	Group 4	P value
Spliting strenght (N/mm^2)	$\bar{x}$	0.52 **A**	0.54 **A**	0.70 **C**	0.63 **B**	0.000
	sd	0.09	0.07	0.09	0.08	-

$\bar{x}$: arithmetic mean, sd: standard deviation, *: lowest value, with different letters (*A, B, C) indicating significant differences in Duncan test results.

Fig. 3 Post-test images of splitting strength test samples (from left to right: Groups 1-4).

The Janka hardness test data, ANOVA P-values, and Duncan test results are presented in Table 6. As shown, the lowest hardness value was measured in Group 1 (21.7 N/mm^2), and the highest was measured in Group 2 (35.8 N/mm^2). The surface hardness of Group 2 increased by 65% compared to the control group. The differences between the groups were statistically significant ($P < 0.001$). The hardness values of wood samples from oak species are generally higher than those of most other wood species. One study reported a Janka hardness of 62 N/mm^2 for the tangential surface of oak (Ayata and Bal, 2019). In other words, the hardness value of the solid wood is much higher. However, in the present study, the hardness value measured only on the top surface of the LVL board, in the 3 mm-thick oak veneer and underlying poplar veneer, was 35.8 N/mm^2.

Tab. 6 Janka hardness test data, ANOVA P value, and Duncan test results.

		Group 1	Group 2	Group 3	Group 4	P value
Janka hardness (N/mm^2)	x̄	21.7 **A**	35.8 **D**	29.5 **C**	25.9 **B**	0.000
	sd	4.6	5.2	3.6	2.8	

x̄: arithmetic mean, sd: standard deviation, *: lowest value, with different letters (*A, B, C, D) indicating significant differences in Duncan test results

The adhesion performance of the poplar veneers in the center of the LVL boards was determined in a tensile-shear test and is presented in Table 7. As seen, both the air-dried and wet test samples exceeded the 1 N/mm^2 limit. This adhesion strength indicated good adhesion between the poplar veneers. Therefore, the percentages of wood fracture or glue failure, as specified in the relevant standard, were not determined. Furthermore, the adhesion strengths between the oak, beech, and eucalyptus veneers on the outer surfaces and the poplar veneer were not calculated because these were the outermost portions of the test samples. Furthermore, the primary purpose of this study was not to evaluate the adhesion performance of poplar veneers with other wood veneers.

Tab. 7 Adhesion strength test data of group 1.

		Air-dried test samples	Wet test samples
Adhesion strength (N/mm^2)	x̄	3.2	1.1
	sd	5.3	3.8

x̄: arithmetic mean, sd: standard deviation.

CONCLUSION

In this study, the mechanical properties of poplar LVL boards produced by bonding oak, beech, and eucalyptus veneer sheets to their top and bottom surfaces (tension and compression zones) were compared with LVL boards produced with all of the layers made of poplar. The findings indicated that the density, modulus of rupture, modulus of elasticity, screw holding capacity, splitting strength (except for the oak group), compressive strength, and Janka hardness values of the LVL boards with oak, beech, and eucalyptus veneers on their top and bottom surfaces were statistically significantly higher than those of the control group LVL boards. These results indicated that the increase in mechanical performance was greater than that achieved by reinforcing LVL boards with synthetic fibers such as glass or carbon fiber. Although glass or carbon fiber provides some reinforcement, it is clear that the increase in strength is not sufficient. Therefore, based on the results of this study, it is recommended to use veneers from a wood species with higher mechanical performance when reinforcing LVL boards produced from poplar or similar tree species.

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