Physical and Mechanical Properties of Hybrid Poplar Laminated Veneer Lumber Produced with Polyol Added pMDI Adhesive

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Improving the performance of laminated veneer lumber can be a key to expanding the value-added use of renewable, fast-growing, low-density poplar raw material. This study evaluated the impact of a commercial neat pMDI (*polymeric methylene diphenyl diisocyanate*) and a pMDI formulation containing 5% polyol (pMDI +5%P) on the physical, mechanical, and bonding properties of laminated veneer lumber (LVL) prepared from poplar (*Populus* × *euramericana* I-214) veneers. Physical properties including the moisture content (9.03% and 8.75%), air-dry density (0.54 g/cm³ and 0.56 g/cm³), thickness (11.1% and 11.3%), and volumetric swelling (after 72 h) (19.9% and 18.9%), were found to be similar to 15-layered LVLs produced from pMDI and pMDI +5%P, respectively. However, mechanical test results showed that bonding quality (4.44 to 5.92 N/mm²) and correspondingly modulus of elasticity (MOE, 7880 to 9410 N/mm²), bending strength (MOR, 73.4 to 90.5 N/mm²), and screw withdrawal capacity (22.6 to 30.6 N/mm²) significantly (at 95% confidence level) increased on the LVLs produced from pMDI +5%P. Additionally, hardness on the surface (3460 to 4000 N), longitudinal (2950 to 3600 N), and parallel hardness (4570 to 5600 N) values of LVLs were increased. However, impact strength decreased from 4.50 to 3.80 kJ/m² with polyol addition. It can be said that this situation stems from an increase in adhesion brittleness upon the addition of polyol.

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INTRODUCTION

The combination of a decrease in forests (especially old growth), ecological constraints, and the increasing demand for multi-story wood buildings, has slowly led to the replacement of solid wood products with engineered wood products (EWPs). Solid wood has many advantages; however, its natural defects, dimensional movement related to moisture, and limited size can restrict its structural use. Engineered wood products help reduce these limitations by providing more uniform properties, better dimensional stability, and more efficient use of fast-growing or lower-grade raw materials. Laminated veneer lumber (LVL), an example of EWP, is produced by bonding veneers parallel to the longitudinal axis. Because of its predictable high performance, LVL is widely used in beams, joists, headers, scaffold planks, and other load-bearing components (Kurt 2010; Xue and Hu 2013; Chen *et al.* 2017; Stark and Cai 2021).

The properties of LVL are shaped by several factors rather than a single variable. Studies report that wood species, veneer density, adhesive type, pressing conditions, loading direction, and layer arrangement all affect final performance. Burdurlu *et al.* (2007) found that laminated beech-poplar materials had higher bending strength and modulus of elasticity than the corresponding solid woods, particularly when the proportion of high-density beech veneers increased. Bal and Bektaş (2012a) also reported that species and load direction had clear effects on LVL bending properties, while adhesive type was less dominant when density differences were considered.

Fast-growing species have an important role in engineered wood production because they can supply industry more continuously and reduce pressure on natural forests. Poplar is one of the most common examples because it grows rapidly, is easy to process, and is widely available. Its main limitation is its relatively low density and lower mechanical properties compared with species such as beech, eucalyptus, birch, bamboo, or hornbeam. Even so, poplar can still be suitable for lightweight engineered applications. Bal and Bektaş (2012a) reported that poplar LVL had lower modulus of rupture (MOR) and modulus of elasticity (MOE) than beech and eucalyptus LVL, but its specific strength values were relatively favorable. Kurt (2010) also found that LVL produced from hybrid poplar clones had higher density, MOR, MOE, compression strength, and glue line shear strength than the corresponding solid woods, primarily due to compaction, adhesive contribution, manufacturing technique, and clone-related differences.

Fast-growing poplar hybrids have been widely investigated as potential raw materials for engineered wood products because their density, mechanical properties, veneer quality, and end-use performance may vary considerably among clones. De Boever *et al.* (2007) reported that selected poplar hybrids showed differences in density, MOR, MOE, and tension wood formation, indicating that clone selection is an important factor for poplar-based LVL production. Veneer quality and hot-pressing parameters are also important in LVL production. Wang and Dai (2005) showed that veneer stress grade and veneer moisture content were dominant factors affecting the stiffness and strength of aspen LVL, while glue spread and platen pressure mainly influenced hot-pressing time and pressing behavior.

Many researchers have sought to improve poplar-based LVL using reinforcement, hybrid layups, cultivar selection, heat treatment, and different adhesive systems. Bal (2014) reinforced poplar LVL by inserting woven glass fibers between poplar veneers with phenol formaldehyde (PF) adhesive and reported improvements in impact bending strength, shear strength, and dimensional stability. Chen *et al.* (2017) produced bamboo-poplar hybrid LVL with PF adhesive and showed that placing bamboo layers on the surfaces increased MOE, MOR, and shear strength. In that study, MOR ranged from about 81.2 to 253 N/mm^2, and MOE ranged from about 11.7 to 25.4 GPa.

Poplar clone and cultivar selection is another route for improving LVL performance. Rahayu *et al.* (2015) produced LVL from 3 mm and 5.25 mm veneers of different poplar cultivars using polyvinyl acetate (PVAc) adhesive. They reported MOR values of about 45 to 58 N/mm^2 and MOE values of 6710 to 9440 N/mm^2. For the I-214 clone, the values were lower, approximately 44.6 N/mm^2 for MOR and 6710 N/mm^2 for MOE, which shows the limited structural potential of this clone compared with stronger cultivars. El Haouzali *et al.* (2020) also reported increment on MOR values 58 to 78 N/mm^2 and MOE values of 6580 to 8760 N/mm^2 for LVL produced from different poplar cultivars.

Another common approach is to combine poplar with denser or stiffer materials. Bal (2016) produced LVL from poplar and eucalyptus veneers using PF adhesive and reported that eucalyptus veneers improved bending properties, impact bending strength, bonding performance, and water resistance. Arabi *et al.* (2024) produced polyurethane (PU)-bonded LVL from hornbeam, poplar, and paulownia. Their results showed that denser hornbeam layers increased density, MOR, MOE, and shear strength. However, alternating denser and lighter layers was more favorable for reducing delamination and cracking under cyclic boil-dry conditions. Kılıç *et al.* (2010) investigated LVL produced from Austrian pine and Lombardy poplar with different layer arrangements and reported that increasing the proportion of pine veneers increased density, bending strength, and modulus of elasticity, whereas poplar-rich combinations showed higher expansion in water.

Adhesive type also affects LVL performance, especially bonding quality, dimensional stability, and resistance to moisture. Formaldehyde-based (urea, UF; melamine-urea, MUF; phenol, PF) and other adhesives (polyvinyl acetate, PVAc; poly urethane, PU; isocyanate-based) have all been used in LVL or related laminated products. Kılıç (2012) investigated PVAc and PU adhesives in beech-poplar laminated materials and indicated that density, porosity, shrinkage, and swelling depended on both species combination and adhesive system. Uysal (2006) compared PF, PVAc, VTKA/PU, and UF adhesives after steam exposure and reported that adhesive selection influenced bonding performance under wet conditions. Among these systems, polymeric diphenylmethane diisocyanate (pMDI) is important because it is formaldehyde-free and has high bonding performance and good moisture resistance. Solt *et al.* (2020) reported that pMDI bonding strength development depends strongly on press temperature, press time, and wood moisture content. Under suitable curing conditions, pMDI bonded veneer joints reached tensile shear strength values of about 6 to 7 N/mm². The authors explained that this behavior is related to reactions between isocyanate groups and water in wood, which form amine and polyurea structures.

Polyol addition can further change the behavior of pMDI-based adhesive systems. Specifications for the polyol used in this work are provided in the Experimental section. Çavuş and Ersin (2023) studied bamboo parallel-strand lumber (PSL) bonded with pMDI and pMDI+5% polyol. The addition of 5% polyol increased MOR from 111.74 N/mm^2 to 187.21 N/mm² and MOE from 21,210 N/mm^2 to 22,434 N/mm². It also reduced thickness swelling and water absorption. However, impact bending strength decreased from 9.20 N/mm^2 to 7.03 N/mm², which suggests that polyol addition may improve static performance and dimensional stability while reducing energy absorption under sudden loading. Hosseinpourpia *et al.* (2022) also reported that pMDI-based polyurethane adhesives prepared with polyols and modified polysaccharides improved viscosity, curing behavior, and tensile shear strength.

Related to previous studies, it's thought that LVL performance can be improved by reinforcing the adhesive performance. Within this scope, the present study considered ready-to-use pMDI formulation containing a limited amount of polyol which offers a comparatively simple adhesive alternative for practical usage. There is limited information regarding the combined effects of this formulation on bonding and accordingly physical and mechanical performance of the wood materials. The aim was to improve dimensional stability, modulus of rupture (MOR), modulus of elasticity (MOE), impact strength, bonding quality, fastener performance, and hardness of the LVL manufactured from hybrid Poplar (*Populus* × *euramericana*) with using polyol contained pMDI adhesive.

EXPERIMENTAL

Wood Material

Hybrid poplar (*Populus x euramericana*) veneers with 1.5-mm thickness were commercially provided from the Düzce region of Türkiye. It was ensured that the purchased veneers were uniform in texture, free from rot, and without defects, such as knots, discoloration, *etc*. It was also ensured that the veneers were dried and had a moisture content between 8 to 10%.

Adhesives and Polyol

This study evaluated the performance of commercial neat pMDI and pMDI binders containing 5% polyol by weight. The polyol-containing pMDI adhesive was purchased from the supplier as a ready-to-use commercial formulation. The pMDI was a brown liquid with a specific gravity of 1.24 and a viscosity of approximately 200 cP at 25 °C. Its boiling point was above 300 °C, its flash point was above 200 °C, and thermal decomposition occurred above 230 °C which were obtained from the supplier. The adhesive was insoluble in water but can react with water, alcohols, amines, acids, and bases.

The polyol (Arcol® Polyol PPG 2000) used in this work was a bifunctional, clear, and colorless polyether polyol according to the supplier, was selected for addition to pMDI. This polyol can react with isocyanates and is commonly used in the production of polyurethane-based materials. Its main technical properties are as follows: density at 20 °C approximately 1.01 g/cm³, hydroxyl number 54.7 to 57.5 mg KOH/g, viscosity at 25 °C 325 to 365 mPa·s, acidity maximum 0.020 mg KOH/g, water content maximum 0.050% by weight, pH 4.5 to 7.5, pour point below -25 °C, boiling point above 300 °C, and flash point of 168 °C, which were obtained from the supplier. pMDI adhesives do not require an additional hardener and are used in several industrial applications, including polyurethane floor coverings, wood-based panel production, cold room panels, and spray insulation systems. Depending on production conditions, both neat pMDI and polyol-added pMDI adhesives are generally applied under hot-pressing conditions. The storage life of these adhesives is approximately 45 days at 20 °C.

LVL Manufacturing

Within the scope of this study, two LVL boards were manufactured for each type of binder. The adhesives were applied to the one surface of 60 cm × 60 cm-sized raw veneers with spread amount per unit area of 250 g/m^2. A 15-layer draft was prepared and pressed at 110 °C for 30 min at a pressure of 15 kg/cm² (Cemil USTA-SSP 180T, Türkiye). The boards were left to conditioning on a flat surface after being taken from the press. The average thickness of the finished boards was found to be around 21.5 mm. For this reason, the thickness of the panels was sanded down to 20 mm by sanding approximately 0.75 mm off each surface using an oscillating sanding machine (Jet/JWDS-2244OSC-M, USA).

Determination of Physical Properties

Moisture content of the samples determined according to ISO 13061-1 (2021) and density of samples were determined according to ISO 13061-2 (2021) standard. Samples were prepared with dimensions of 20 mm × 20 mm × 30 mm and measured with accuracy of 0.001 mm using a comparator gauge (Mitutoyo, Japan). Sample weights were measured with the accuracy of 0.01 g using a precision balance (Radwag, Poland). For these properties, 8 samples of each type of adhesive were tested.

Volumetric swelling was determined according to ISO 13061-16 (2025). For this purpose, samples were prepared with dimensions of 20 mm × 50 mm × 50 mm and placed in distilled water, at 20±2 °C, while in a dry state. Measurements were taken by 5 points on the wide surface of samples and 2 points for sides by using a digital comparator gauge (Mitutoyo, Japan). Volume measurements were taken at 4, 24, 48, and 72 h.

Determination of Bending Strength

Bending strength (MOR) was determined according to the ISO 13061-3 (2021) standard. Samples measuring 20 mm × 20 mm × 360 mm were prepared and tested on a universal testing machine (Lloyd, USA) with a capacity of 100 kN, using a 15h support span. To determine the MOR, 20 samples of each adhesive were prepared. The samples were placed flatwise during the three-point bending test. The results were calculated using Eq. 1,

$$MOR = \frac{3 \times P_{max} \times l}{2 \times b \times h^2} \quad (1)$$

where MOR is the modulus of rupture (N/mm^2), P_{max} is the maximum load (N), l is the span (mm), b is the width of the test piece (mm), and h is the height of the test piece (mm).

Determination of Modulus of Elasticity

The MOE was determined in accordance with the principles of the ISO 13061-4 (2021) standard. The MOE values were obtained from MOR testing on the same samples. Calculations were made according to Eq. 2,

$$MOE = \frac{P \times l^3}{4 \times b \times h^3 \times f} \quad (2)$$

where MOE is the modulus of elasticity (N/mm²), P is the difference between the upper and lower limit loads (N), l is the span length (mm), b is the specimen width (mm), h is the specimen thickness (mm), and f is the deformation difference between the upper and lower limit loads (mm).

Determination of Impact Strength

The impact strength was determined using the ISO 13061-10 (2021) standard. Test specimens were prepared with dimensions of 20 mm × 20 mm × 300 mm, and tests were conducted with a support span of 240 mm. To determine impact strength, a total of 32 samples were prepared for each binder. Calculations were performed according to Eq. 3,

$$Impact\ strength\ (A) = \frac{Q}{b \times h} \quad (3)$$

where A is impact strength (kJ/m²), Q is energy expended (kJ), b is sample width (m), and h is sample thickness (m).

Determination of Screw Withdrawal Capacity

The screw withdrawal capacity was determined according to the TS EN 13446 (2005) standard. Tests were performed on the wide surfaces of samples measuring 20 mm × 50 mm × 50 mm.

A pre-hole with 2-mm diameter was drilled into the samples prior to screw application. A 4-mm diameter screw was used for the test procedure and applied throughout the thickness of the sample. 20 samples were prepared for each adhesive to determine screw withdrawal capacity. Calculations were performed according to Eq. 4,

$$Screw\ withdrawal\ capacity\ (f) = \frac{F_{max}}{d \times l_p} \quad (4)$$

where f is the screw withdrawal capacity (N/mm²), F_{max} is the maximum pull-out load (N), d is the screw diameter (mm), and l_p is the screw penetration depth (mm).

Determination of Static Hardness

The ISO 13061-12 (2021) standard was used to determine static hardness. Hardness tests were performed on three surfaces of 20 mm × 50 mm × 50 mm specimens by applying a 5.64-mm diameter steel ball at a speed of 6 mm/min until it penetrated halfway. To determine static hardness, a total of 18 samples were prepared for each type of adhesive. The tests were applied to the surface, parallel and perpendicular to the grain direction of the LVLs. Calculations were made according to Eq. 5,

$$H = K \times F \quad (5)$$

where H is the static hardness value (N), F is the maximum load (N), and K is the coefficient value according to the test depth (1 for 5.64 mm).

Determination of Bonding Quality

TS 3969 EN 314-1 (1998), and TS EN 314-2 (1999) standards were used to determine the bonding quality. Samples were sized 20 mm × 25 mm × 100 mm as per the standard requirements. Saw cuts were opened on the samples, and the width of the opening was 25 mm. Before pretreatment, possible shear-break areas of the samples were measured with an accuracy of 0.1 mm. The standards suggest pretreatment related to usage area. In this study "Class 1: dry interior" class was chosen and the samples were immersed in the water at 20 °C for 24 h.

The shear-load was applied parallel to the grain (longitudinal) direction with a constant rate of motion that breaking occurred within 30 (± 10) s. To determine bonding quality 15 samples prepared and tested for each type of adhesive. The tension-shear strength was calculated according to Eq. 6,

$$Tension - shear\ strength\ (TSS) = \frac{P_{max}}{w \times l} \quad (6)$$

where TSS is the tension-shear strength (N/mm²), P_{max} is the maximum break load (N), w is the width of the breaking area (mm), and l is the length of the breaking area (mm).

Statistical Analysis

To evaluate the effects of adhesive systems on the mechanical and physical properties of LVL, independent samples t-tests were performed using IBM SPSS Statistics 23. Prior to the analysis, the normality of the data was assessed using the Shapiro-Wilk test, while the homogeneity of variances was evaluated using Levene's test. For groups meeting the normality assumption ($p > 0.05$), differences between adhesive systems were evaluated using independent samples t-tests at a 95% confidence level.

RESULTS AND DISCUSSION

Physical Tests

The moisture content of the samples was 9.03% for pMDI and 8.75% for pMDI+5%P. The air-dry density values were 0.54 and 0.56 g/cm³, respectively. Although the pMDI+5%P group had a slightly higher density, the difference between the groups was not statistically significant ($p > 0.05$). Therefore, the addition of polyol (5%P) did not cause a significant increase in density. Studies showed that LVL density is mainly affected by wood species, layer arrangement, adhesive type, and pressing conditions (Kılıç 2012; Bal 2014; Arabi *et al.* 2024). The density values in this study were higher than some values reported for poplar-based LVL. For example, Bal (2014) reported a density of about 0.40 g/cm³ for poplar LVL produced with phenol formaldehyde adhesive, and Burdurlu *et al.* (2007) also reported lower density values for poplar-based laminated materials, produced by using PVAc adhesive, compared with beech-containing groups. This difference may be related to the adhesive amount, applying, pressing conditions, and the structure of lamination used in this study.

Thickness swelling increased with water immersion time in both groups. For pMDI, the thickness swelling values were 6.85%, 9.62%, 10.80%, and 11.11% after 4, 24, 48, and 72 h, respectively. For pMDI + 5%P, the values were 7.22%, 9.87%, 10.69%, and 11.26%. The pMDI group had numerically lower thickness swelling at 4, 24, and 72 h, while pMDI+5%P showed a slightly lower value at 48 h. However, thickness swelling of the pMDI and pMDI+5%P groups did not show a statistically significant difference ($p>0.05$) for any of the immersion times. pMDI generally gave slightly better thickness swelling resistance, but the difference was small and not fully consistent. The limited difference between the two adhesive groups may be related to the similar densities, the similar initial moisture contents of the panels and the water-resistant character of pMDI. Swelling behavior in LVL is influenced by species, porosity, adhesive type, and layer arrangement (Kılıç 2012; Arabi *et al.* 2024).

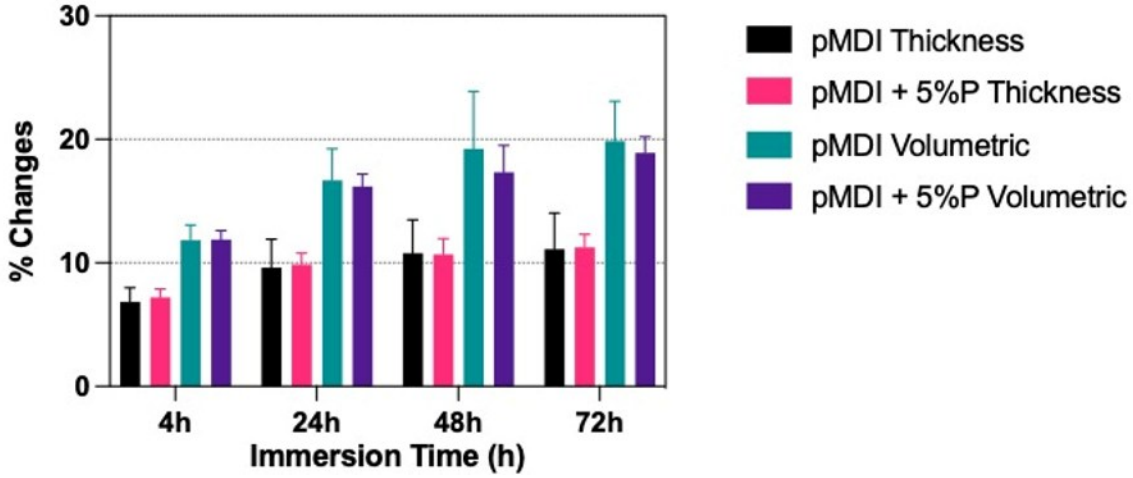

Fig. 1. Changes in thickness swelling and volumetric swelling of LVL samples during water immersion; the error bars indicate the standard deviation.

Volumetric swelling showed a slightly different trend. The volumetric swelling values for pMDI were 11.8%, 16.7%, 19.2%, and 19.9% after 4, 24, 48, and 72 h, respectively. For pMDI+5%P, the values were 11.88%, 16.20%, 17.33%, and 18.90% (Fig.

1). The two groups were almost the same after 4 h, but pMDI+5%P showed lower volumetric swelling after 24, 48, and 72 h. There wasn't any statistically significant difference ($p>0.05$) between two adhesive groups. Thus, the data didn't provide statistical evidence that the polyol containing pMDI adhesive changes volumetric swelling under the test conditions. In the literature, Çavuş and Ersin (2023), found that pMDI+5% polyol reduced thickness swelling and water absorption in bamboo PSL compared with pMDI alone. However, in this study, the improvement was more evident in volumetric swelling than in thickness swelling.

Overall, the performance of the PMDI adhesive was better in thickness swelling tests, while the PMDI+5%P adhesive showed better results than pMDI adhesive in volumetric swelling tests. Consequently, it was concluded that there was no statistically significant difference between the PMDI and PMDI+5%P groups in terms of physical properties. The change in thickness and volumetric swelling over time is presented in Fig. 1.

Mechanical Test Results

Flexural properties

Mechanical and selected physical properties are presented in Table 1. The variation in MOR is shown in Fig. 2, while the variation in MOE is shown in Fig. 3. The pMDI+5%P adhesive system improved the static bending performance of the laminated material. The mechanical improvement was much greater than the small density increase, the main reason for this improvement appears to be better bond-line structure rather than densification alone.

The MOE value increased from 7880 N/mm² in the pMDI group to 9410 N/mm² in the pMDI+5%P group, corresponding to an increase of approximately 19.4%. The MOR also increased from 73.4 to 90.5 N/mm², representing an improvement of about 23.4%. Statistically significant differences were determined between the groups for both MOE and MOR ($p < 0.05$). Density-normalized comparisons supported the observed mechanical improvement. Specific the MOE increased from approximately 14.6 to 16.8 N/mm^2, corresponding to an increase of about 15.1%, while specific MOR increased from approximately 136 to 162 N/mm^2, corresponding to an increase of about 19.0%. Thus, the improvements in MOE and MOR were proportionally greater than the small increase in mean density. Statistical significance was not evaluated separately for these ratios, and they are therefore presented as descriptive comparisons. Therefore, although no direct bond-line characterization or adhesive performance tests were conducted within the scope of this study, the observed increases in MOE and MOR may be associated with improved bond-line quality, enhanced adhesive-veneer interaction, and more efficient stress transfer between veneer layers.

The results are comparable with previous LVL studies. Bal and Bektaş (2012a) reported that LVLs manufactured from poplar, beech, and eucalyptus veneers bonded with UF, MUF, and PF adhesives exhibited MOR values ranging from 68.1 to 100.1 N/mm² under flatwise loading conditions, while the corresponding MOE values varied between 6480 and 9650 N/mm². Kurt (2010) also reported MOR values between 75.1 and 89.3 N/mm² and MOE values between 6300 N/mm² and 7580 N/mm² for hybrid poplar LVL bonded with MUF adhesive. The findings in this study indicate competitive bending performance compared with poplar-based LVL materials reported in the literature.

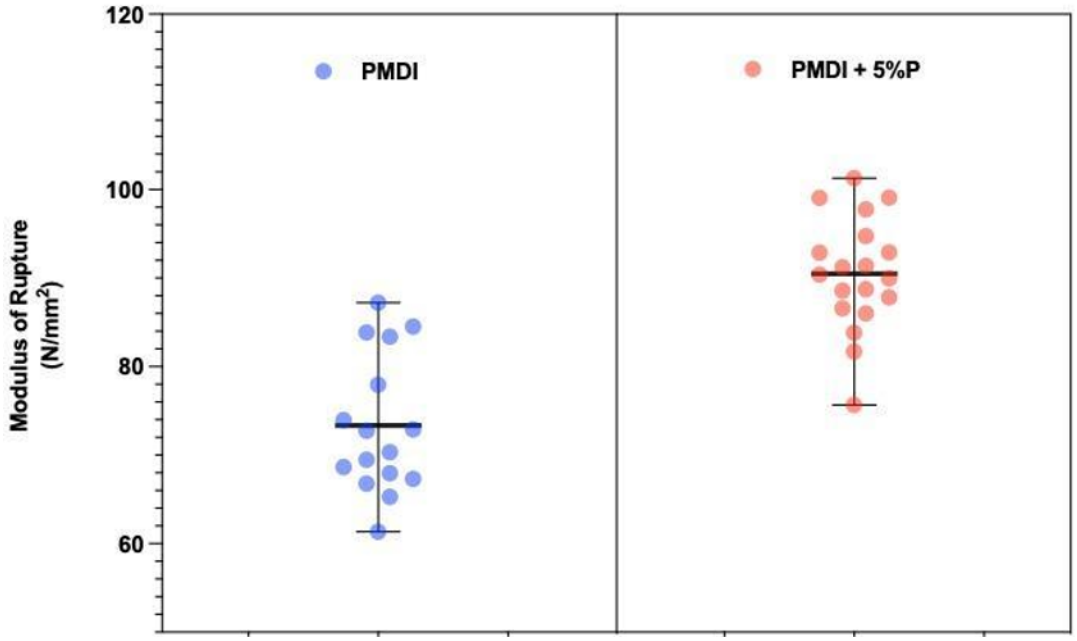

Fig. 2. Effect of adhesive type on the modulus of rupture of LVL samples

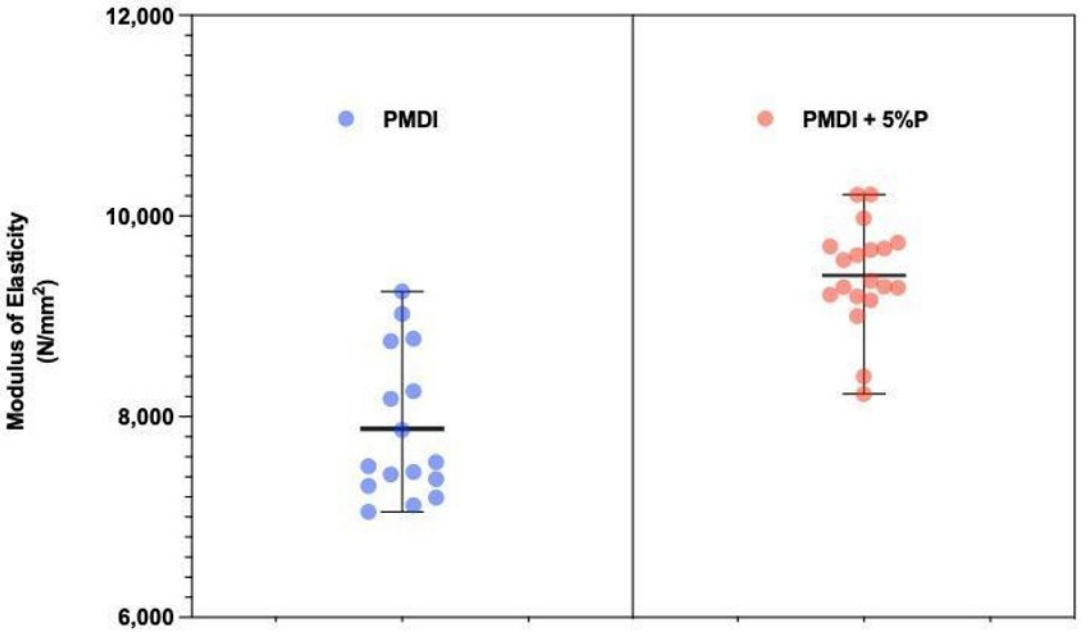

Fig. 3. Effect of adhesive type on the modulus of elasticity of LVL samples

Similar trends were also reported in studies using modified adhesive systems or reinforced laminated structures. Çavuş and Ersin (2023) found that pMDI+5% polyol increased MOR and MOE in bamboo parallel-strand lumber. These findings support the idea that bending performance depends on adhesive quality, veneer arrangement, and stress distribution as well as density (Nazerian and Ghalehno 2011).

The positive effect of pMDI+5%P may also be related to adhesive chemistry. Solt *et al.* (2020) reported that pMDI bond development depends on moisture content, press temperature, and press time, while Hosseinpourpia *et al.* (2022) showed that pMDI-based

polyurethane adhesives with polyols can improve viscosity, curing behavior, and shear strength. Thus, the increase in MOE and MOR in this study may be linked to a more developed adhesive network and stronger bonding between veneer layers. However, since the properties related to the adhesive's bond structure were not examined in this study, no definitive evidence can be provided.

Table 1. Some Physical and Mechanical Data of the Tests

Test	N	Adhesive	X_{min}	X_{max}	X_{Avg}	S
ρ_{12}	8	pMDI	0.49	0.58	0.54[a]	0.032
	8	pMDI+5%p	0.54	0.57	0.56[a]	0.012
MC (%)	8	pMDI	8.08	10.16	9.03[a]	0.75
	8	pMDI+5%p	8.37	9.38	8.75[a]	0.37
MOE	16	pMDI	7052.24	9246.91	7880.05[a]	727.09
	19	pMDI+5%p	8226	10212.44	9408.88[b]	514.72
MOR	16	pMDI	65.27	87.23	73.35[a]	7.8
	19	pMDI+5%p	81.69	101.30	90.50[b]	6.41
IS	25	pMDI	4.33	7.25	4.50[a]	1.46
	31	pMDI+5%p	2.83	4.87	3.80[b]	0.58
SWC	18	pMDI	18.76	27.92	22.57[a]	2.60
	15	pMDI+5%p	26.17	36.74	30.63[b]	3.06
BQ	15	pMDI	3.95	4.90	4.44[a]	0.31
	15	pMDI+5%p	5.31	6.40	5.92[b]	0.30
H_S	18	pMDI	2786.22	4261.16	3462.82[a]	385.30
	15	pMDI+5%p	3450.85	4529.48	3996.40[b]	338.63
H_L	18	pMDI	1769.46	3710.17	2946.40[a]	543.11
	15	pMDI+5%p	2983.02	4285.51	3596.86[b]	286.19
$H_{//}$	18	pMDI	3497.16	5181.15	4570.43[a]	512.57
	15	pMDI+5%p	4989.86	6686.36	5600.20[b]	472.67

N: Number of samples, X_{min}: Minimum value X_{max}: Maximum value X_{Avg}: Average value
ρ_{12}: Air-dry density (g/cm^3), MC: Moisture content (%), MOE: Modulus of elasticity (N/mm^2), MOR: Modulus of rupture (N/mm^2), IS: Impact strength (kJ/m^2), SWC: Screw withdrawal capacity (N/mm^2), BQ: Bonding quality (N/mm^2), H_S: Hardness of surface (N), H_L: Longitudinal hardness (N), $H_{//}$: Parallel hardness (N); * Differences in the sample numbers were caused by factors such as measurement errors, sample size incompatibilities, and non-standard sample measurements.

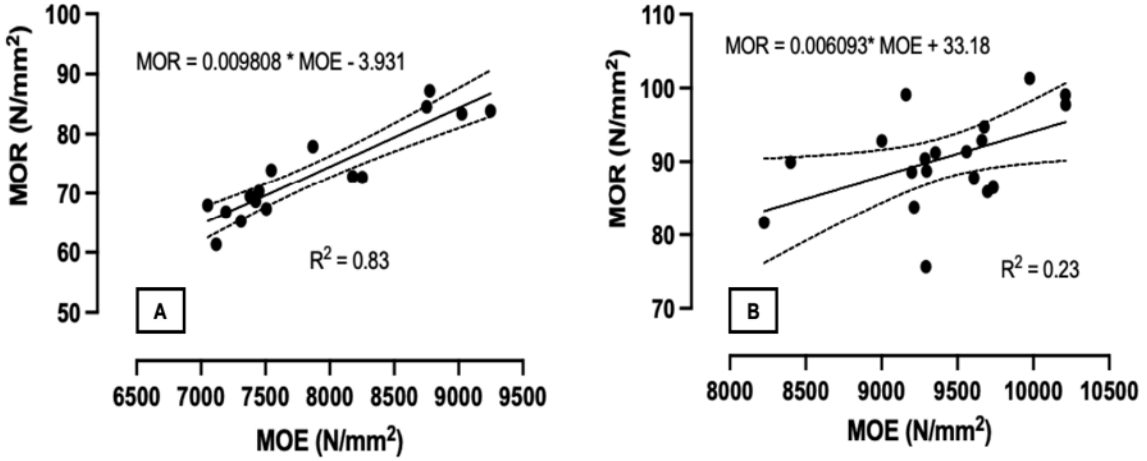

Fig. 4. Relationship between MOE and MOR of LVL samples bonded with pMDI and pMDI+5%P adhesives (A is represented control groups, B is represented as a 5% polyol added groups)

The relationship between MOE and MOR is shown in Fig. 4. Graph A shows the regression data for the pMDI adhesive, while Graph B shows the data for the pMDI+5%P adhesive. Regression equation for pMDI was MOR=0.009808*MOE-3.931, while equation for pMDI+5%P was MOR=0.006093*MOE+33.18.

The pMDI group showed a strong positive relationship between MOE and MOR ($R^2 = 0.83$, n = 16), whereas this relationship was weaker for pMDI+5%P ($R^2 = 0.23$, n = 19). Although polyol addition increased the mean MOE and MOR values, the increases were not proportional among all specimens. Higher MOE indicates greater stiffness and resistance to elastic deformation rather than a loss of elasticity. Çavuş and Ersin (2023) similarly reported increased MOR and MOE after adding 5% polyol to pMDI. In addition, Li *et al.* (2017) and Hosseinpourpia *et al.* (2022) showed that polyol composition can affect the curing and bonding performance of pMDI-based adhesive systems. However, these studies do not directly demonstrate that polyol addition changes the MOE-MOR correlation. Because adhesive rheology and bond-line characteristics were not measured, the lower R^2 value of the pMDI+5%P group should be interpreted as greater within-group variation rather than as a confirmed chemical effect of polyol addition.

Impact strength

Impact strength decreased with the addition of 5% polyol to pMDI. The IS value decreased from 4.50 kJ/m² in the pMDI group to 3.80 kJ/m² in the pMDI+5%P group, corresponding to a reduction of approximately 15.56%. Statistically significant differences were determined among the groups ($p < 0.05$), and the variation in impact strength is shown in Fig. 5.

This result indicates that although the pMDI+5%P adhesive system improved static mechanical properties, such as MOR, MOE, bonding quality, screw withdrawal capacity, and hardness, it reduced the ability of the laminated composite material to absorb energy under sudden impact loading. The decrease in impact strength should be evaluated separately from static bending properties because impact loading reflects energy absorption under a short loading time. Bal and Bektaş (2012b) reported that tree species and loading direction significantly affected impact bending strength of LVL, while adhesive type was not significant, and they noted that glue lines may behave more fragile than solid wood under dynamic loading.

The decrease in impact strength could not be determined directly from the present experiments. The reduction may be related to changes in bond-line stiffness or deformation behavior after polyol addition. Such changes could improve static load transfer while limiting energy absorption under sudden loading (Dinwoodie 2000; Thelandersson and Larsen 2003; Shumlsky and Jones 2014). This interpretation is consistent with the findings of Çavuş and Ersin (2023), who reported that pMDI+5% polyol increased MOR and MOE in bamboo parallel-strand lumber, while impact bending strength decreased from 9.20 N/mm² in the pMDI group to 7.03 N/mm² in the pMDI+5%P group.

In addition, Solt *et al.* (2020) reported that pMDI bond strength development is strongly influenced by press temperature, press time, and wood moisture content, and that proper curing can lead to a more complete polymer network and higher tensile shear strength. This supports the view that improved bond-line development can enhance static bonding performance, while the resulting stiffer structure may reduce impact energy absorption. In contrast, Bal (2014) reported that woven glass fiber reinforcement improved the impact bending strength of poplar LVL because the reinforcement acted as a crack-

bridging and impact-distribution layer. This suggests that adhesive modification and reinforcement materials may affect impact behavior through different mechanisms.

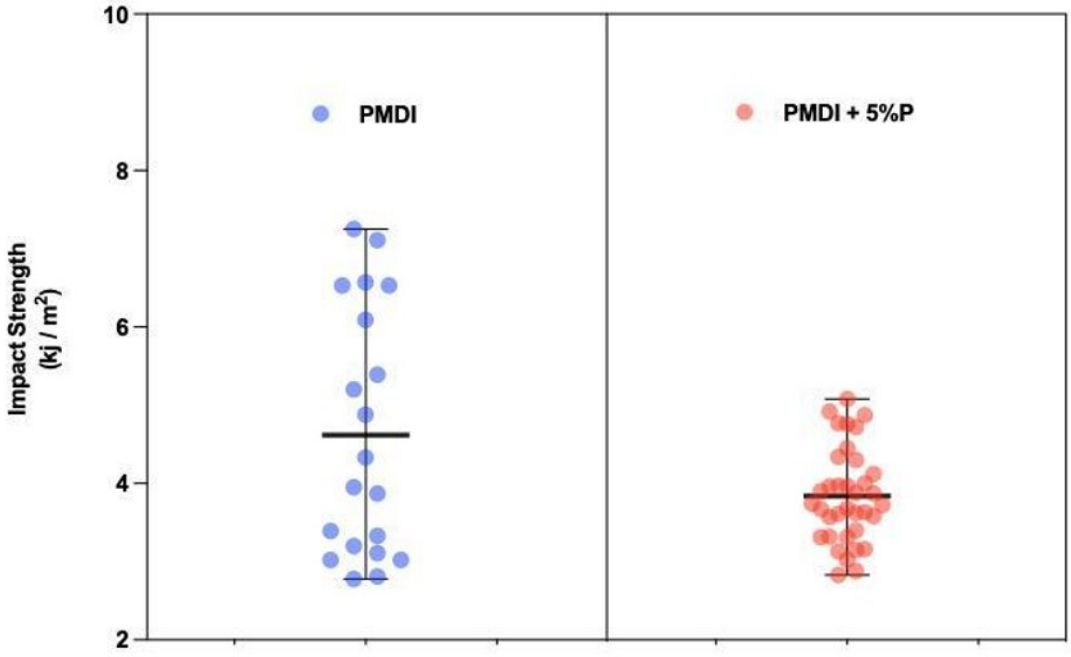

Fig. 5. Effect of adhesive type on the impact strength of LVL samples

Bonding quality,

Bonding quality was significantly improved with the addition of 5% polyol to pMDI. The BQ value increased from 4.44 N/mm² in the pMDI group to 5.92 N/mm² in the pMDI+5%P group, corresponding to an increase of approximately 33.3%. Statistically significant differences were determined among the groups ($p < 0.05$), and the differences in bonding quality are shown in Fig. 6. The values obtained for both types of adhesives met the 1 N/mm² threshold specified in the EN 314-2 standard. Since the average values exceeded this requirement, the percentage of wood appearing after failure was not measured separately. The pMDI+5%P formulation resulted in higher bonding quality than the pMDI group under the tested conditions. This difference may be associated with changes in curing or adhesive-veneer interaction, although the underlying mechanism was not directly investigated . Besides, Solt *et al.* (2020) reported that pMDI bond strength development is strongly affected by press temperature, press time, and wood moisture content, emphasizing that curing conditions play a critical role in the final bonding performance of pMDI-bonded wood composites.

The improvement in bonding quality is also consistent with the findings of Hosseinpourpia *et al.* (2022), who reported that pMDI-based polyurethane wood adhesives containing polyols and modified polysaccharides showed improved viscosity, curing behavior, and tensile shear strength. Their results support the view that hydroxyl-functional additives can positively affect the performance of pMDI-based adhesive systems. The positive effect of polyol addition can also be interpreted through pMDI-polyol adhesive chemistry. Li *et al.* (2017) showed that the NCO/OH ratio was a key factor controlling dry and wet shear strength in pMDI-polyol plywood adhesives. The work also showed that an optimum polyol ratio improved bonding performance, while excessive cross-linking could reduce wet durability. The NCO/OH ratio was not determined in this study. However, it is

assumed that the findings could theoretically be explained by this mechanism. Similarly, Çavuş and Ersin (2023) reported that pMDI+5% polyol improved several physical and mechanical properties of bamboo parallel-strand lumber, including MOR and MOE, compared with pMDI alone. This supports the interpretation that polyol modification can enhance adhesive performance and improve load transfer between bonded elements. Sonnenschein and Wendt (2005) also reported that pMDI/polyol mixtures may affect board properties through phase segregation, dispersion, and interfacial behavior. This supports the view that the higher bonding quality in the pMDI+5%P group may be related to changes in adhesive network formation and wood-adhesive interaction. They also indicated that the curing conditions in this study and interfacial aspects such as adhesive droplet size, penetration could affect the bonding quality in another study (Sonnenschein *et al.* 2005). Therefore different production parameters can be tried in the further studies to improve the LVL performance.

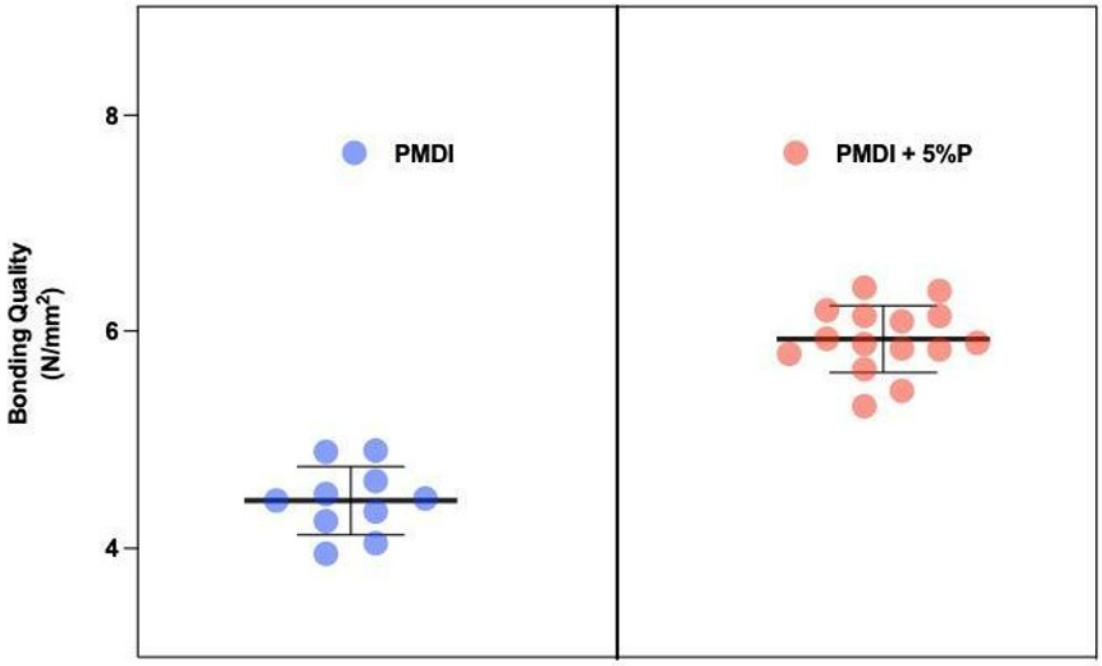

Fig. 6. Effect of adhesive type on the bonding quality of LVL samples

Screw withdrawal capacity

The screw withdrawal capacity was determined as 22.6 N/mm² for the pMDI group and 30.6 N/mm² for the pMDI+5%P group. The differences in SWC among groups are shown in Fig. 7. The addition of polyol increased the SWC value approximately 35.7%. The results of the t-test indicate a statistically significant difference ($p < 0.05$) between the groups. This increase indicates that the surface and internal bonding structure of the pMDI+5%P group became more resistant to screw withdrawal forces. The improvement in SWC can be associated with increased density, better interlayer bonding, and enhanced surface hardness. In the study by Çavuş and Ersin (2023), it was reported that screw withdrawal capacity was affected more by fiber orientation and the anisotropic structure of the material than by adhesive type. In the same study, the screw withdrawal capacity values in the tangential, radial, and transverse directions were reported as 43.6, 47.2, and 35.2 N/mm² for the pMDI group, and 47.2, 48.6, and 32.5 N/mm² for the pMDI+5% polyol group, respectively. However, in the present study, because both bonding quality and

hardness values increased in the pMDI+5%P group, the increase in SWC may be related to improved bond-line integrity and greater strength to localized deformation around the screw threads. Because screw withdrawal capacity is partly controlled by local crushing and surface strength around the screw, the increase in hardness observed in the pMDI+5%P group may have contributed to the higher screw withdrawal capacity. Shukla and Kamdem (2008) reported that LVL made from low-density hardwoods showed higher surface hardness than solid wood, supporting the relationship between lamination, surface strength, and fastener performance.

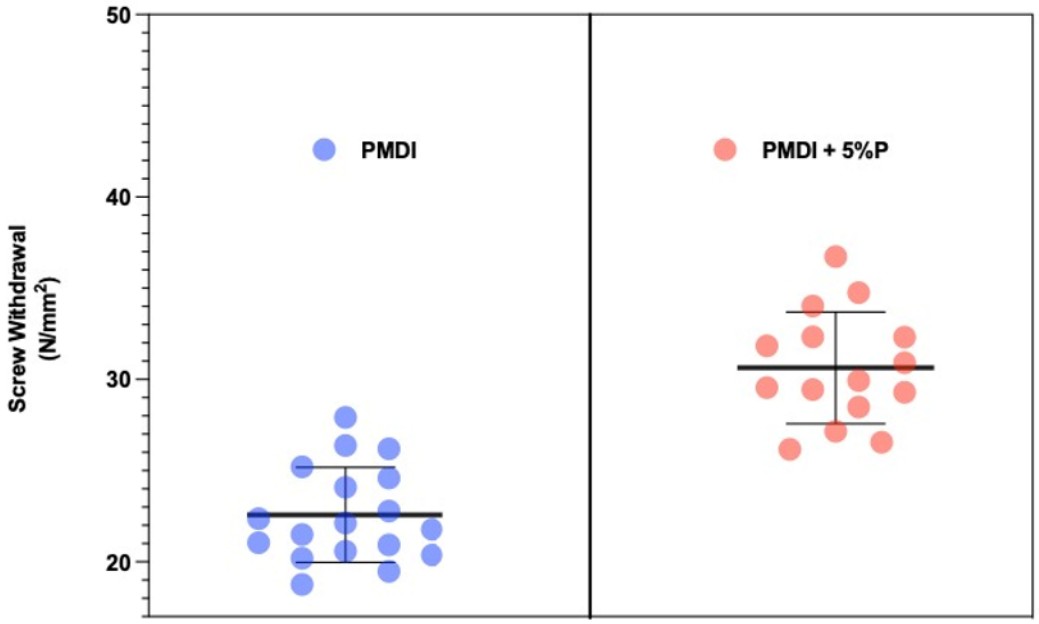

Fig. 7. Effect of adhesive type on the screw withdrawal capacity of LVL samples

Static hardness

Hardness values were evaluated in three different directions. The pMDI+5%P group showed higher hardness values than the pMDI group in all directions, and statistically significant differences were determined among the groups ($p < 0.05$). The variation in hardness values among the groups is shown in Fig. 8. Surface hardness increased from 3460 to 4000 N, corresponding to an increase of approximately 15.4%. longitudinal hardness increased from 2950 to 3597 N, representing an increase of approximately 22.1%. Parallel hardness increased from 4570 to 5600 N, corresponding to an increase of approximately 22.5%. These results indicate that the pMDI+5%P adhesive system improved not only the flexural properties but also the surface and directional hardness properties of the laminated veneer lumber. The increase in hardness may be associated with improved bonding quality, higher density, and enhanced strength of the material structure to localized indentation. Shukla and Kamdem (2008) reported that the surface hardness of LVL produced from low-density hardwoods was considerably higher than that of solid wood, with silver maple LVL showing surface hardness values in the range of 4.92 to 5.31 kN. Similarly, the increased hardness values obtained in the pMDI+5%P group in the present study suggest that polyol addition contributed positively to surface strength and mechanical consolidation.

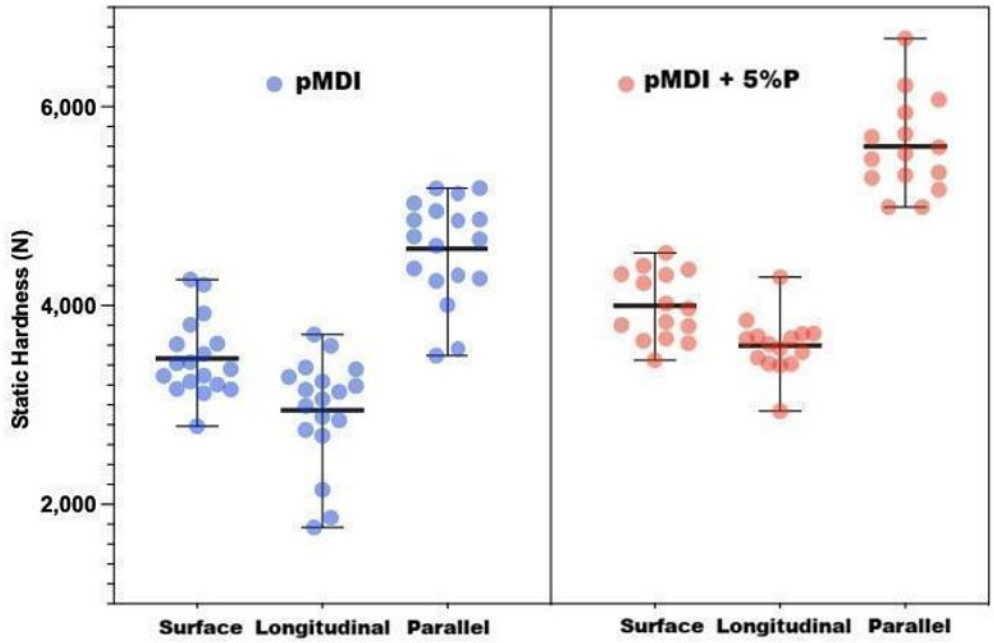

Fig. 8. Effect of adhesive type on the surface, longitudinal and parallel static hardness of LVL samples

CONCLUSIONS

1. Physical properties such as density, thickness, and volumetric swelling were not statistically affected by adhesive type. Although there were differences in adhesive amount for thickness and width, similar results in physical properties showed that there was good bonding for each adhesive and samples moved as a single piece, especially during water immersion.
2. Bonding quality and screw withdrawal capacity increased notably in the pMDI +5%P group, indicating better bond-line performance and improved resistance to localized withdrawal forces.
3. All investigated (static) mechanical properties were increased with polyol addition except impact strength. The findings indicated that energy absorption capacity was reduced and samples got more brittle after addition against the impact loads.

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