Correlation between non-destructive assessment of wood veneers and the resulting laminated veneer lumber

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Abstract. This study investigated correlations between the mechanical properties of individual red maple *(Acer rubrum)* veneers and that of associated laminated veneer lumber (LVL). Veneers with an average thickness of 3.5 mm, width of 304 mm, and length of 2.44 m, were first subjected to a nondestructive test (NDT) using stress wave analysis. Dynamic modulus of elasticity (MOE_d) was used to classify 480 veneers into four equal groups: high-grade, medium-grade, low-grade, and a mixed group. Each LVL consisted of 12 veneers bonded with polyurethane (PUR) adhesive. All LVL billets were evaluated nondestructively to determine their dynamic modulus of elasticity. Two different measurement systems were employed: a Fakopp Microsecond Timer was used for a time-of-flight approach and a Hitman HM200 (resonance acoustics approach) applied the longitudinal stress wave method and assessed its reliability for predicting the mechanical performance of LVL billets. A strong correlation ($r = 0.85$ and $R^2 = 0.73$) was found between the average $MOE_{dVeneer}$ of veneers and that of the LVL billets (MOE_{dLVL}). There was a strong correlation between MOE_d from the Hitman HM200 device ($MOE_{dHitman}$) and that from the Fakopp device ($MOE_{dFakopp}$) ($r = 0.93$ and $R^2 = 0.86$).

Keywords: Hardwood; Red maple; Mechanical properties; Nondestructive evaluation (NDE); Dynamic modulus of elasticity (MOE_d); Longitudinal stress wave method; Fakopp; Hitman

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Introduction

The concept of green building has gained significant traction in recent years (Pajchrowski et al. 2014; Xue and Hu 2013). However, the increasing reliance on fast-growing plantation trees has resulted in smaller logs with lower wood quality, making it difficult for traditional solid lumber to meet modern construction demands (Gao and Gong 2021; McGavin and Leggate 2019). In response to these challenges, engineered wood products (EWPs) have emerged as viable alternatives. The push toward sustainable construction has driven innovations in EWPs such as laminated veneer lumber (LVL), cross-laminated timber (CLT), and glulam, offering superior physical and mechanical performance compared to traditional solid lumber (Gong 2019). Corrugated wood-based panels, constructed from fibers and veneers, represent a novel solution that improves both the structural performance and resource efficiency of EWPs (Lamichhane et al. 2025**.** These products promote greater resource efficiency and lower carbon emissions, aligning well with contemporary sustainable building practices (Winchester and Reilly 2020). In addition, techniques like densification have been shown to enhance mechanical characteristics, particularly stiffness and elasticity (Pradhan et al. 2024)

The orthotropic nature of wood must be taken into consideration when studying its behavior. Wood properties such as density, grain structure, and mechanical properties can vary significantly across different species, environmental conditions, and even among individual pieces from the same tree (Arriaga et al. 2023). These variations highlight the need for developing advanced methods to ensure reliable performance of EWPs like LVL in structural applications.

Since the 1960s, nondestructive evaluation (NDE) techniques have gained considerable attention, particularly for mechanical grading of wood (Divós and Tanaka 2005). NDE is also widely used to detect voids, irregularities, and other common defects in wood products (Del Menezzi et al. 2013). A major advantage of NDE is its ability to assess the mechanical and physical properties of wood without causing any damage, making it a valuable tool for wood quality assessment (Ross 2015; Miclea et al. 2002; Turkot et al. 2020; Liu et al. 2006).

Numerous studies have employed NDE to classify veneers, lumber, and logs for manufacturing EWPs. Teles et al. (2010) reported a strong coefficient ($R^2 = 0.95$) between the dynamic MOE of glulam and its laminae using the transverse vibration method. Similarly, Wang et al. (2003) demonstrated that ultrasonic wave propagation time and the corresponding MOE of red maple veneers were closely related to the strength and stiffness of LVL billets. Ross et al. (2004) further observed that the dynamic MOE values of red maple veneers followed a normal distribution, validating their applicability for LVL manufacturing.

While individual NDE methods have proven effective in evaluating the mechanical properties of wood, integrating multiple techniques can enhance the precision and reliability of the results (Divos and Tanaka 1997; Vössing and Niederleithinger 2018; Kloiber et al. 2016). Cavalli and Togni (2013) employed a combination of flexural and longitudinal vibration tests, stress wave transmission measurements, and Pilodyn penetration tests to evaluate the mechanical properties of silver fir timber, emphasizing that a single method was often insufficient for a comprehensive evaluation. Similarly, Chen and Guo (2016) combined stress wave timing with resistance drilling tests to evaluate the mechanical properties of Chinese fir and elm, finding strong linear correlations between nondestructive test parameters and key mechanical properties. This underscores the importance of exploring various NDT technologies to overcome the limitations of individual methods and achieve more reliable results.

Previous studies have investigated the potential of red maple (*Acer rubrum* L.) for structural applications, citing its favorable physical and mechanical properties (Ross et al. 2004; Kimmel and Janowiak 1995; Wang et al. 2004). However, red maple remains unexplored for use in EWPs due to limited commercial processing. Notably, few nondestructive evaluation studies have specifically targeted red maple, and most existing research relies on a single NDE technique.

To address this gap, the present research contributes to ongoing efforts to expand the market for this underutilized hardwood species by employing nondestructive test methods to accurately predict the structural performance of associated EWPs such as LVL.

In this study, we examined the relationships between the mechanical properties of individual veneers ($MOE_{dVeneer}$) and the overall structural performance of LVL (MOE_{dLVL}) using the longitudinal stress wave method. Two different measurement systems were employed: time-of-flight (ToF) approach, using a Fakopp Microsecond Timer, and resonance acoustics approach, using a Hitman HM200. The findings from this study contribute to a deeper understanding of how veneer-level mechanical characteristics affect the overall stiffness of LVL. The results have practical significance from an industrial perspective, as they may inform strategies for optimizing veneer selection and layer configuration, thereby minimizing material waste and enabling the production of high-performance veneer-based products.

Materials and methods

Veneer

A total of 480 red maple veneer sheets (0.304 by 2.43 m (1 by 8 ft)) were selected for LVL fabrication from a larger population of 553 sheets reported in a previous study by Belaidi et al. (2025b). Seventy-three veneers were removed from the test because of prior damage. All veneer sheets were obtained from Great Lake Veneer (Marion, WI, USA). Prior to nondestructive evaluations, the density of all 480 veneers was determined by measuring their length, width, thickness, and mass (Table 1). The veneers were conditioned at 12% moisture content in a controlled environment to achieve a target equilibrium moisture content before the fabrication of LVL billets.

Grading process

The veneers were visually graded according to the International Hardwood Veneer Grading Rules (Redman 2020). The grading process, which considered various factors such as the number, size, and types of knots, checks, and splits, was used to assign each veneer a grade of A, B, C, or D. The grading process is explained in detail by Belaidi et al. (2025b).

LVL Fabrication and grading

To manufacture LVL billets with a target thickness of 38 mm (1.5 in), 12 layers of veneer were bonded using a one-component polyurethane (PUR) adhesive. LOCTITE UR5153 and its corresponding primer, LOCTITE PR3105 PURBOND (Henkel, Henrico, VA, USA) were applied using rollers to ensure uniform distribution on the bonding surface. The target application rate for this adhesive was 40 lb/1,000 ft^2 (200g/m^2). After applying the adhesive, the weighed veneers revealed an average application rate of approximately 220 g/m^2.

LOCTITE UR5153 had an opening time of 30 minutes and required a pressing time of 1 hour (Belaidi et al. 2025a). The manufacturing process involved pressing four LVL billets simultaneously at 150 psi. A total of 40 LVL billets were produced and trimmed, and the average dimensions (length, mass and width) were recorded to determine the density of LVL billets (Table 2).

To quantify the grading for the LVL billets, numerical values were assigned to each letter grade: 4 for Grade A, 3 for Grade B, 2 for Grade C, and 1 for Grade D; since each LVL billet was fabricated from veneers of different grades, it was not possible to assign a single letter grade to each veneer. These numerical values representing the grades were then summed to develop a single number representing the grade of the LVL billet. For example, if an LVL contained 6 Grade A veneers, 2 Grade B veneers, 3 Grade C veneers, and 1 Grade D veneer, the grading number was calculated as follows: (6×A) + (2×B) + (3×C) + (1×D) ≥ (6×4) + (2×3) + (3×2) + (1×1) = 37

The minimum possible grade number was 12, when all 12 veneers were Grade D, while the maximum number was 48, if all 12 veneers were Grade A.

Table 1. Average dimensions of red maple veneers.

Number of veneers measured	Thickness (mm)	Width (mm)	Length (mm)	Density (kg/m³)
480	3.55	304.04	2441.96	584

Table 2. Average dimensions of LVL billets.

Number of LVL	Thickness (mm)	Width (mm)	Length (mm)	Density (kg/m³)
40	39.96	280.50	2420.30	697

Nondestructive Characterization of LVL Billets

Time of Flight measurements

The veneers were nondestructively tested using the stress wave method to determine the dynamic modulus of elasticity. Each veneer was clamped at both ends using a specialized fixture (Figure 1a).

Ross (2015) noted that additional support was added under the veneer to maintain alignment and prevent damage at the contact point, which could affect the accuracy of the results. Each veneer was struck three times using an impact pendulum, and a portable stress wave timer, the Fakopp Microsecond Timer (Fakopp Enterprise, Hungary), was used to measure the transit time of the stress wave traveling from one end to the other. The average transit time, measured from three different longitudinal locations, was used to measure the stress wave velocity, using Equation 1, and the dynamic modulus of elasticity was then determined according to Equation 2.

$$\nu = L/\mathrm{t} \quad [1]$$

$$\mathrm{MOE_d} = \rho * \nu^2 \quad [2]$$

Where L is the length of the veneer (m), t is the transit time measured using the Fakopp device (s), ρ is the density of the veneer (kg/m^3), and ν is the velocity (m/s).

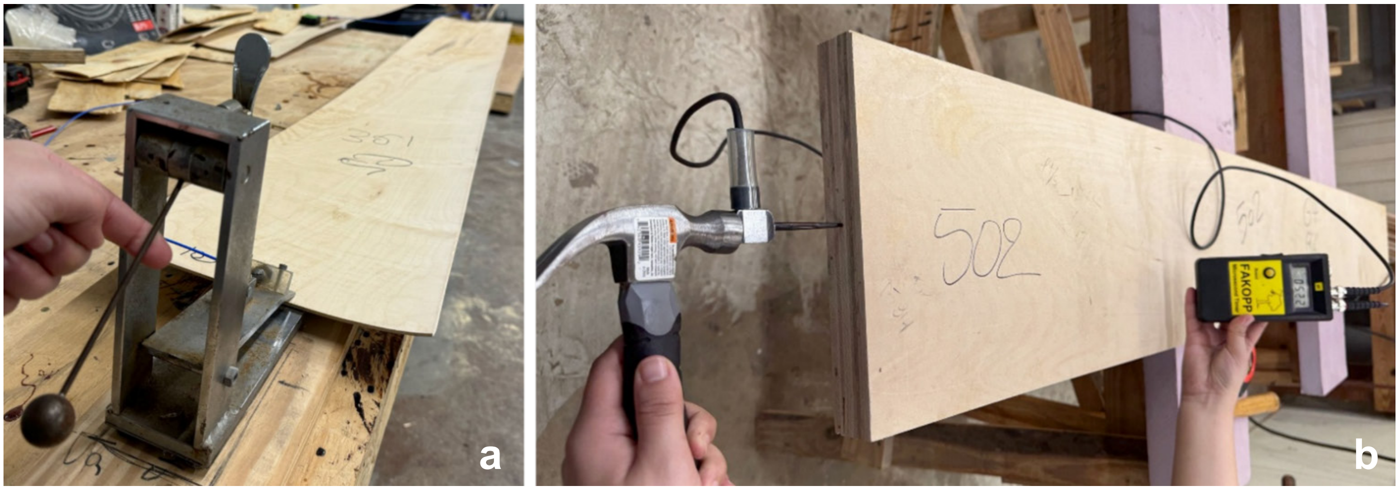

Figure 1. Setup for the stress wave measurement (a) using built-in pendulum; (b) using pins.

The same nondestructive method was applied to determine the dynamic modulus of elasticity of the LVL billets. Each billet was placed flatwise on two sawhorses, as shown in Figure 1(b). Pins were nailed at both ends of the billet, with the start pin struck by a small hammer to generate a stress wave that traveled the length of the billet. The Fakopp device recorded the transit time. The average transit time, measured from two different longitudinal locations, was used to determine the stress wave velocity and dynamic modulus of elasticity according to Equations 1 and 2, respectively.

Resonant acoustic measurement

Each LVL billet was placed flatwise on two sawhorses, positioned one-quarter of the total length from each end. A thin foam layer was placed between the billet and the sawhorses to reduce damping effects and improve measurement accuracy. A portable nondestructive device, the Hitman HM200 (Fibre-gen, Christchurch, New Zealand), was pressed against one end of the LVL billet, while the billet was hit with a hammer to generate longitudinal vibration. The Hitman device measures the stress wave velocity in the LVL billet. Average stress wave velocity, measured from two different longitudinal locations was used to calculate the dynamic modulus of elasticity, using Equation 2.

The Hitman HM200 was not suitable for the veneers due to their thinness, since the required contact area for the device exceeded the veneer thickness. While the vibration was propagated by the hammer, the small contact area could prevent the Hitman device from detecting the vibration, and as a result, affect the velocity measurement.

Statistical analysis

The statistical analyses were conducted using OriginPro software (Northampton, MA), at the significance level of 0.05 ($\alpha = 0.05$).

Results and discussion

Stress wave properties of the veneer

Dynamic modulus of elasticity (MOE_d) for the 480 veneers ranged from 10 to 26 GPa. The average MOE_d of the veneers was 19.10 GPa (± 2.97 GPa) and a coefficient of variance (COV) of 15.55%. According to Kolmogorov-Smirnov normality test, the resulting p-value 0.94 (>0.05), indicated that MOE_d values were normally distributed. The skewness of MOE_d was 0.0408, suggesting an approximate symmetric distribution. The visual grading distribution of the selected 480 veneers is shown in Figure 2.

Based on the MOE_d results, all 480 veneer samples were arranged in ascending order, and then evenly divided into three groups of 160 veneers each, as shown in Figure 3. The first

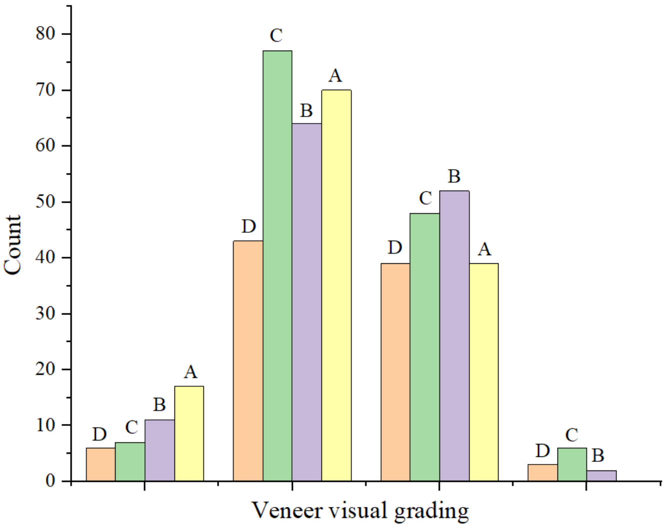

Figure 2. Distribution of the visual grades of 480 red maple veneer (letters on each bar indicate the assigned visual grade).

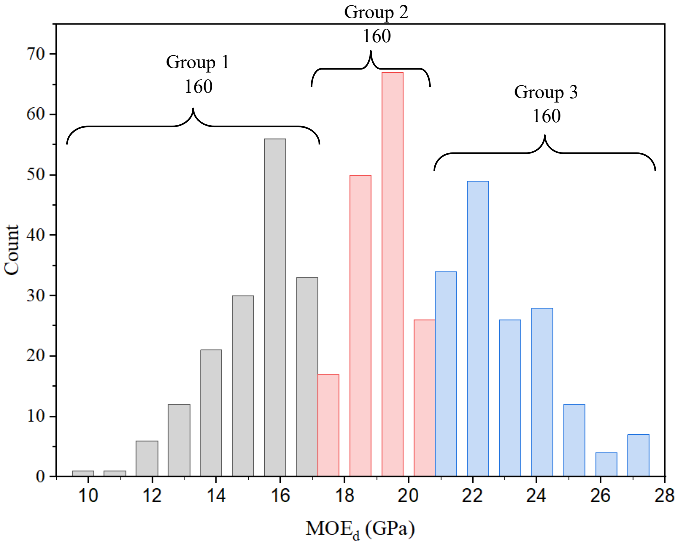

Figure 3. Distribution of MOE$_d$ into three equal groups.

group had MOE$_d$ values ranging from 10.73 to 17.79 GPa, the second group from 17.80 to 20.46 GPa, and the third group from 20.51 to 26.48 GPa. According to the MOE$_d$ values, the first group included high-MOE$_d$ veneers, the second contained medium-MOE$_d$ veneers, and the third consisted of low-MOE$_d$ veneers. An additional group, the fourth group, was created using a mix of veneers ranging from low to high MOE$_d$ values.

To ensure a representative distribution in the fourth group, each of the three original groups, ordered in ascending MOE$_d$, was subdivided into 10 subgroups of 16 veneers each (Figure 4). From each subgroup of 16 veneers, 4 veneers were randomly selected, resulting in 40 veneers from each original group and a total of 120 from all three groups. These 120 veneers, covering a wide range of MOE$_d$ values from low to high, were assigned to the fourth group. This selection resulted in four groups, each consisting of 120 veneers, ensuring an equal number across all groups.

The average MOE$_d$ of these 120 veneers in the fourth group was 19.05 GPa, which was similar to the average MOE$_d$ of all 480 veneers (Figure 5). The p-value of 0.52 (>0.05) obtained from Shapiro-Wilk normality test indicated a normal distribution for MOE$_d$ values. This confirmed that selecting 120 veneers with a normal distribution for the fourth group accurately represented the entire population.

Veneers from each group were used to manufacture 12-layer LVL billets, with 10 billets produced for each group, to investigate the impact of veneer MOE$_d$ on the structural performance of LVL. For the first three groups, 12 layers were randomly selected from each group, using a random number generator method, and stacked together, regardless of their MOE$_d$ and grade, to fabricate the LVL billet. For the fourth group, which was a combination of the first three groups, high-MOE$_d$ veneers from the third group were placed on the outer layers of the LVL, low-MOE$_d$ veneers from the first group were placed at the center, and medium-MOE$_d$ veneers from the second group were placed in between.

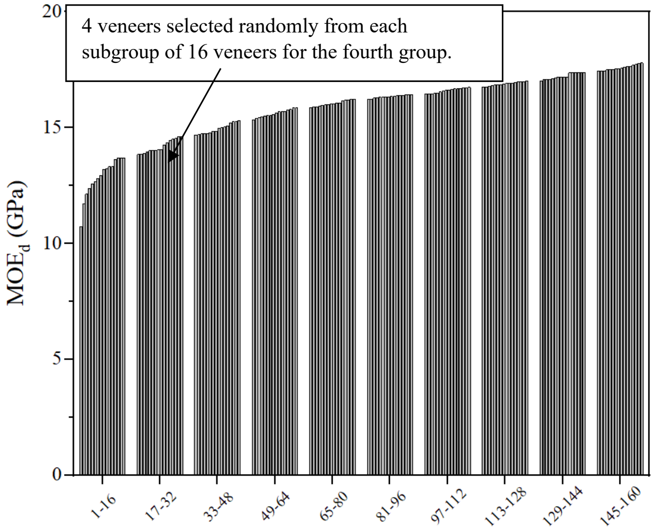

Figure 4. Sorting the veneers of the first group into 10 subgroups of 16 veneers each for random selection of 4 veneers from each subgroup into the fourth group.

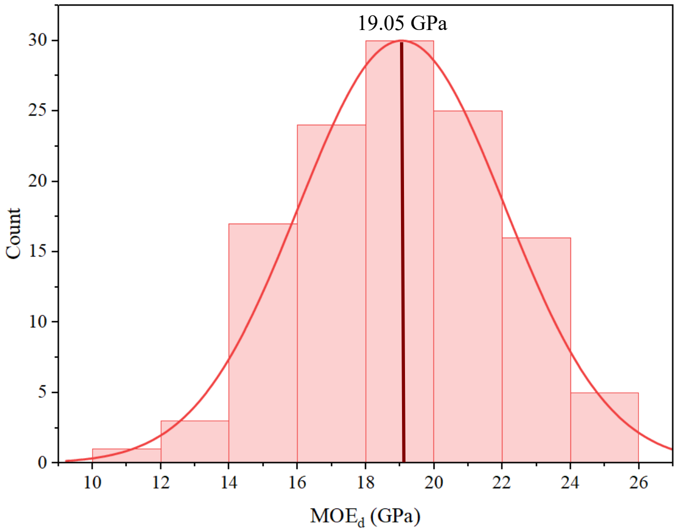

Figure 5. Distribution of the dynamic modulus of elasticity of 120 red maple veneers for the fourth group.

Stress Wave Properties of LVL billets

The distribution of the dynamic modulus of elasticity for the 40 LVL billets, obtained using the Fakopp device (Figure 6a), ranged from 13 to 17 GPa, with an average of 15.63 GPa (± 1.03 GPa) and a coefficient of variance (COV) of 6.5%. A

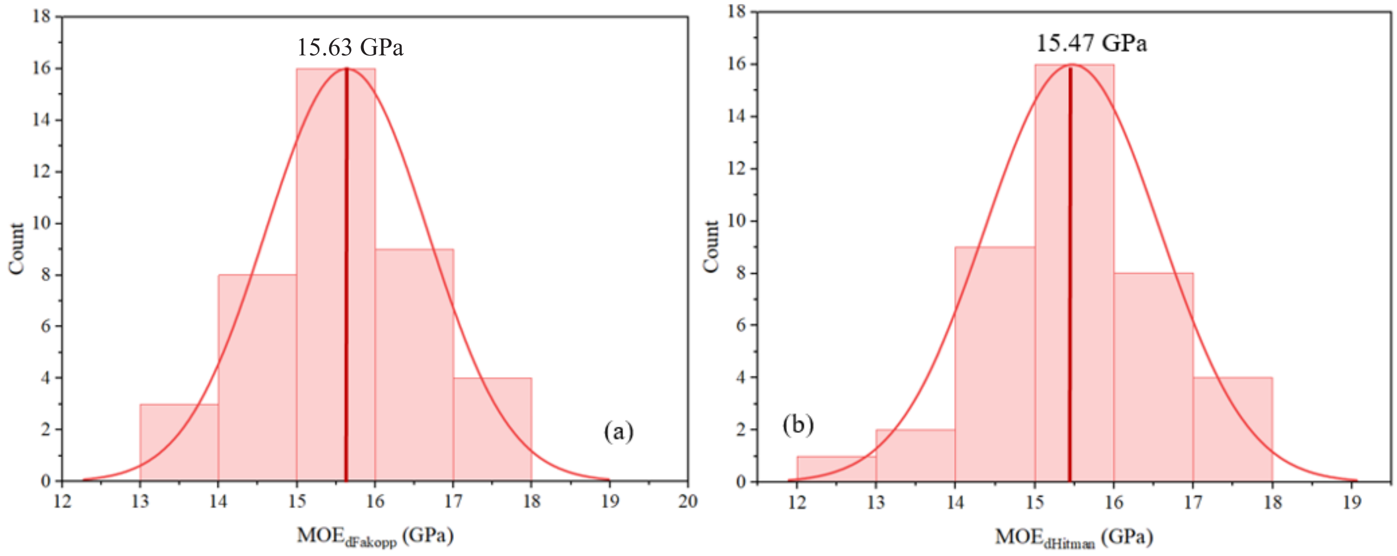

Figure 6. Distribution of the MOE$_d$ using (a)Fakopp (MOE$_{dFakopp}$,); (b) Hitman (MOE$_{dHitman}$) measurements of 40 LVL billets.

Shapiro-Wilk normality test was conducted on the MOE$_{dFakopp}$ values using OriginPro software, resulting in a p-value of 0.84 (> 0.05), indicating a normal distribution for MOE$_{dFakopp}$ values.

Figure 6b presents the distribution of the dynamic MOE of the same 40 LVL billets evaluated using the Hitman device. The results ranged from 12 to 17 GPa, with a mean value of 15.47 GPa (± 1.10 GPa) and a coefficient of variation of 7.11%. The Shapiro-Wilk test for MOE$_{dHitman}$ values yielded a p-value of 0.9, indicating a normal distribution.

Both nondestructive testing devices yielded similar mean values for the dynamic MOE of the LVL. This consistency suggests that both devices provided a reliable evaluation of the mechanical properties of the LVL billets. A regression analysis and paired t-test were conducted using OriginPro software to investigate whether these observed similarities were statistically significant (Figure 7).

There was a very strong correlation between MOE$_{dFakopp}$ and MOE$_{dHitman}$ (R^2 of 0.83, and Pearson's r of 0.93). The resulting p-value from the paired t-test was 0.0144 (< 0.05), suggesting that the difference between dynamic MOE obtained using these two devices was statistically significant at $\alpha = 0.05$. However, since the difference is minimal (0.16 GPa), the devices are still interchangeable.

The stress wave velocity parallel to the grain generally ranges from 3500 to 5000 m/s for different species, including red maple (Dackermann et al. 2014; Nowak et al. 2021). Figure 8 presents the distribution of stress wave velocity for both measurement methods. The results for the Fakopp device ranged from 4400 to 5100 m/s, with an average of 4732.89 m/s (± 140.17 m/s) and a coefficient of variation of 2.96% (Figure 12a). Similarly, velocity with the Hitman device (Figure 12b) was 4708.07 m/s (± 164.05 m/s), and a coefficient of variation of 3.48%. According to the Shapiro-Wilk normality test, the results of p-values for stress wave and longitudinal were 0.87 and 0.86, respectively, suggesting a normal distribution. These findings ranged from 4300 to 5100 m/s and are consistent with previous reports by Dackermann et al. (2014).

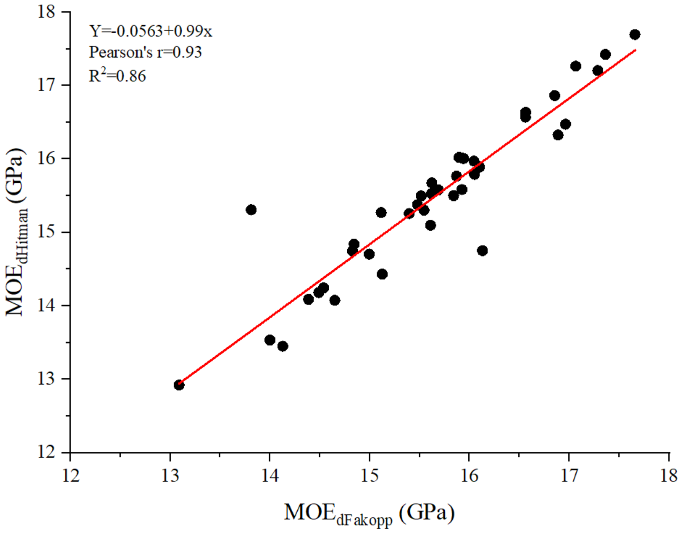

Figure 7. Relationship between MOE$_{dFakopp}$ and MOE$_{dHitman}$.

Effect of the nondestructive evaluation of the veneers on the dynamic MOE of LVL

This section investigates the relationship between the dynamic MOE of the veneer obtained using the stress wave method

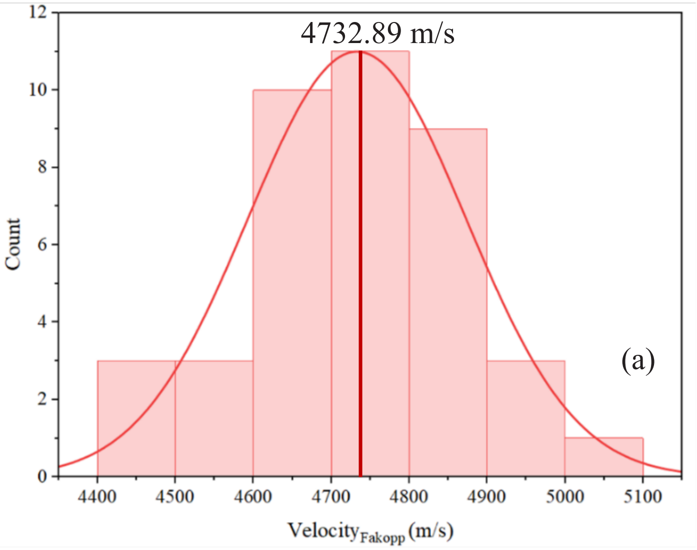

Figure 8. Distribution of the stress wave velocity: (a) V_{Fakopp}; (b) V_{Hitman} of 40 LVL billets.

with the Fakopp device and the dynamic MOE of the final LVL beams obtained through the same measurement method presented in Figure 6a. Although both measurement methods yielded comparable results, the Fakopp device was selected over the Hitman device due to its lower coefficient of variation (6.5% compared to 7%), making it a more reliable choice.

A regression analysis was then conducted using OriginPro software to assess the relationship between the dynamic MOE of LVL and the average dynamic MOE of associated veneers, as presented in Figure 9. The results showed a strong positive correlation between MOE_{dLVL} and $MOE_{dVeneer}$, with a Pearson's r of 0.85. The coefficient of determination ($R^2 = 0.73$) suggested that the MOE_d of the veneers explained 73% of the variability in MOE_{dLVL}.

Similar trends were observed in previous studies, where the stress wave properties of veneers positively influenced the properties of LVL (Del Menezzi et al. 2013). Additionally, Kunesh (1978) found a strong correlation (0.92) between longitudinal stiffness of veneer measured with a dynamic stress wave system and the tensile strength of associated LVL, as well as a high correlation ($R^2 = 0.91$) with LVL bending strength. Wang et al. (2003) found that the dynamic MOE of red maple veneer was well correlated with the bending strength of LVL billets.

Similarly, Zhou et al. (2013) found a strong correlation between MOEd of the veneers and that of the LVL ($R^2 = 0.93$).

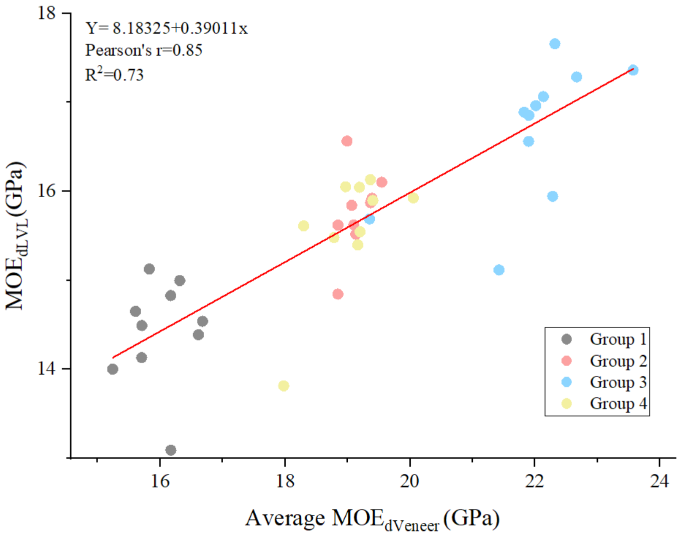

Figure 9. Relationship between MOE_{dLVL} and the average dynamic MOE of 12 associated veneers ($MOE_{dVeneer}$).

Nondestructive testing of LVL billets and their veneers indicated that MOE of the veneers was higher than that of the LVL billets (Table 3), while the velocity of the veneers was slightly greater than that of the LVL billets, even though the same Fakopp NDT method, was used for both materials. The difference could be related to the fixture used for the measurement. We used a fixture and a pendulum for veneers, while pins were used for LVL billets. The other difference could be the composite veneer/glueline composition of the LVL billet, since it is a laminated product; thus, the MOE for the LVL billets is not simply an average of the MOE of the veneers, but also includes the glueline. Conversely, the density of the LVL billets was higher than the average density of associated veneers. The results contrast with the findings of Del Menezzi et al. (2013),

Table 3. — Comparison of density, stress wave velocity, and MOE between LVL and veneers across different MOE groups.

Group	Density				Velocity				Dynamic MOE			
	Veneer		LVL		Veneer		LVL		Veneer		LVL	
	Mean[a]	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
1	571 (12.38)	2.17	692 (32.83)	4.74	5282 (99.37)	1.88	4565 (77.84)	1.7	16 (0.44)	2.75	14 (0.55)	3.95
2	583 (9.26)	1.59	705 (15.98)	2.26	5749 (49.46)	0.86	4728 (72.39)	1.53	19 (0.23)	1.23	15.75 (0.42)	2.66
3	594 (7.86)	2.32	697 (19.51)	4.51	6108 (75.19)	1.23	4904 (57.11)	1.16	22.19 (0.55)	2.50	16.76 (0.70)	4.22
4	584 (7.86)	1.34	695 (19.51)	2.81	5697 (87.58)	1.54	4734 (65.96)	1.39	19.03 (0.55)	2.92	15.58 (0.64)	4.12

[a] Values represent the means of 120 samples per group while numbers in parentheses represent one standard deviation. COV=coefficient of variation (%).

which observed that the stress wave velocity in the veneers was similar to that in the billets, while the dynamic modulus of elasticity of the billets was higher compared to the veneers.

The comparison between the veneers and LVL billets revealed consistent results across all groups. The MOE of the LVL billets in each group was 12.5% to 24.47% lower than that of the corresponding veneers, with the highest reduction occurring in Group 3.

Opposite results were observed in previous studies (Zhou et al. 2013; Del Menezzi et al. 2013), where MOE of LVL billets was higher than that of the corresponding veneers. This difference could be related to the way the stress wave was introduced into the specimen during testing. The wave in the veneers, which were tightened to a steel fixture using a bolt, was generated by releasing a pendulum that struck the fixture, while the wave for LVL billets was produced by directly hitting a steel pin embedded into the billet. Although the same testing method was used, differences in setup may have influenced wave propagation and the resulting MOE values.

Similarly, stress wave velocity was consistently lower by 13.6% to 19.7% in LVL billets than in veneers, with the higher reduction observed in Group 3. This difference may or may not be attributed to the increased thickness of LVL billets. Several studies have investigated the impact of veneer thickness on the dynamic properties of LVL. De Melo and Del Menezzi (2014) reported that veneer thickness had a significant effect only for specimens tested in the flatwise position, where panels made with thinner veneers exhibited a higher modulus of elasticity. However, Purba et al. (2019) found that the highest static MOE and MOR were associated with the LVL made from 3 mm to 4.2 mm thick veneers, and the lowest MOR was found for the LVL made of the thickest veneer. Previous studies have also found that increasing veneer thickness tends to reduce the shear strength and shear modulus of LVL, particularly when tested in the edgewise direction (Ebihara 1981; Pot et al. 2015).

On the other hand, some studies have reported opposing results, suggesting that increased veneer thickness does not necessarily lead to reduced mechanical performance of the LVL. For instance, a study conducted by Girardon et al. (2016) found that the veneer thickness and bending direction did not significantly influence the average MOE, but rather contributed to greater variability in MOE values. Similarly, Rahayu et al. (2015), examined LVL made from poplar veneers of varying thicknesses and reported that the flatwise MOE was lower than the edgewise MOE, while veneer thickness had no significant effect on the modulus of elasticity.

Therefore, while the effect of veneer thickness on MOE remains uncertain, it may not be the primary factor influencing the observed differences in the dynamic properties of veneer and LVL; other factors could also contribute to these variations. Conversely, the density of LVL billets was higher than that of veneers, as the percentage increase varied from 17.3% to 21.2%, with the highest increase occurring in Group 1. This increase can be attributed to the addition of the adhesive, which has a density of 1.12 g/cm^3 (Belaidi et al. 2025a)— which is significantly higher than that of the veneers (0.58 g/cm^3)—and can penetrate the porous structure of red maple veneers. In addition, the compression applied during the manufacturing process could reduce the material's volume, leading to densification. Similarly, Zhou et al. (2013) reported that the density of veneers was lower than that of the LVL boards.

When comparing the different groups, a clear trend was observed in which veneers with higher MOE_d resulted in LVL with higher MOE_d. As presented in Table 3, LVL fabricated with Group 1 veneers, which had the lowest MOE_d (16 GPa), exhibited the lowest MOE_d (14 GPa), while those fabricated with Group 3 veneers, with the highest MOE_d (22 GPa), indicated the highest MOE_d (16 GPa). Stress wave velocity followed a similar pattern, increasing from Group 1 (5282 m/s in veneers, 4565 m/s in LVL) to Group 3 (6108 m/s in veneers, 4904 m/s in LVL). Furthermore, density results varied slightly, with Group 2 having the highest LVL density (704 Kg/m^3), while Group 4 had moderate values for both veneers and LVL.

The mixed group, in which high-grade veneers were placed on the outer layers while medium—and low-grade veneers formed the core, had a MOE_{dLVL} and $MOE_{dVeneer}$ closer to those of Group 2 (medium grade).

These findings highlight the significant effect of MOE of the veneer on LVL performance. Veneers with higher MOE resulted in LVL billets with high MOE_d, while billets fabricated with low-MOE veneers showed lower MOE_d values. A similar conclusion has been reported by Pu and Tang (1997) confirming that veneer quality directly influenced the mechanical properties of LVL billets.

A study carried out by Harding and Orange (1998), on LVL made from *Pinus radiata* found that the lay-up sequence had little to no effect on the physical and mechanical performance of the LVL. A similar conclusion was drawn by Lara Palma and Ballarin (2011) in their study on LVL made from *Eucalyptus grandis*, finding no evidence that the placement of lower-quality veneer on the surface layers affected the performance of the wood panels.

Effect of veneer density and stress wave velocity on MOE_{dLVL}

Veneer density and stress wave velocity are key factors influencing the dynamic modulus of elasticity of the LVL, which directly affects the performance and reliability of the final product. The effect of density and stress wave velocity of veneers on the MOE_{dLVL} was investigated through regression analysis, as shown in Figure 10, using OriginPro software.

Table 4 provides a detailed summary of the statistical results. The regression analysis for density of veneer showed a moderate correlation, with a Pearson's r of 0.62 and R^2 value of 0.38, indicating that density explains 38% of the variation in MOE_{dLVL}. The relationship is statistically significant, as shown by an F-value of 23.61 and a p-value of <0.0001.

In comparison, velocity shows a stronger correlation with MOE_{dLVL}, with a Pearson's r of 0.81 and an R² value of 0.66,

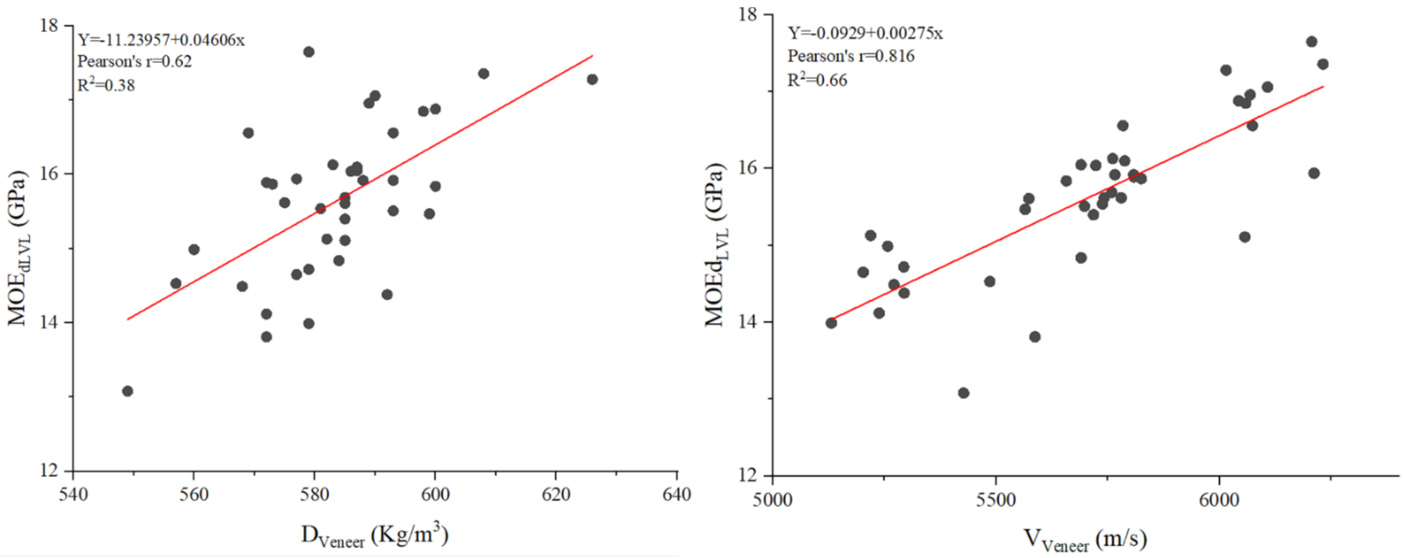

Figure 10. Relationship between density and velocity of veneers with the dynamic modulus of elasticity of LVL.

Table 4. —Regression results of velocity and density on MOE_{dLVL}

MOE_{dLVL}	Equation of regression	Pearson's r	R^2	F value	P value
Density (kg/m^3)	Y= -11.23957+0.04606x	0.62	0.38	23.61493	<0.0001*
Velocity (m/s)	Y= -0.0929+0.00275x	0.81	0.66	76.04058	<0.0001*

* Significant at ≤ 0.05

meaning that 66% of the variation in MOE_{dLVL} can be attributed to velocity. The higher F-value of 76.04 and the p-value of <0.0001 further confirm the statistical significance of this relationship. These results suggest that while both density and velocity influence MOE_{dLVL}, velocity is a more dominant predictor.

Figure 11 presents the regression analysis between the stress wave velocity (V_{LVL}) and the density of the LVL (D_{LVL}) using OriginPro software. The results revealed a very weak correlation, with a Pearson's r of -0.135 and a coefficient of determination of 0.018.

Similar findings were reported by Zhou et al. (2017), who observed a weak correlation between velocity and density of poplar veneer. This can be explained by the fact that density reflects the proportion of solid cell material present in the wood structure (Zhou et al. 2017; Machado et al. 2014). However, several studies (Lasserre et al. 2009; Hernández 2007; Zhou et al. 2017; Hasegawa et al. 2011) have highlighted that wave velocity can be influenced by other factors, including microfibril angle, grain angle, and fiber length, which affect the propagation of the stress wave. Furthermore, Machado et al. (2014) reported that this weak correlation highly depends on the species.

Effect of the Veneer visual grade on the mechanical properties of LVL

Based on the visual grading of veneers, a grading score was assigned to each 12-layer LVL billet. The distribution of LVL billet grading score for the four groups is presented in Figure 12. The grading scores ranged from 24 to 36, indicating that most billets were composed of mid-range veneer grades (B and C), with fewer high-quality grade A veneers or low-quality grade D veneers. The variability observed within each group may be attributed to the random arrangement of veneers during the manufacturing process of LVL billets, leading to differences in the final grading scores.

It was expected that LVL billets made with Group 3 veneers, which had the highest MOE_d, would achieve higher grading scores, while those fabricated with Group 1 veneers would exhibit the lowest grading scores due to their use of veneers with the lowest MOE_d. The grading numbers for LVL billets made with Group 2 and Group 4 veneers were expected to fall between those of groups 1 and 3. However, the actual distribution of grading numbers suggests that most LVL billets fell within the medium range, from 24 to 36.

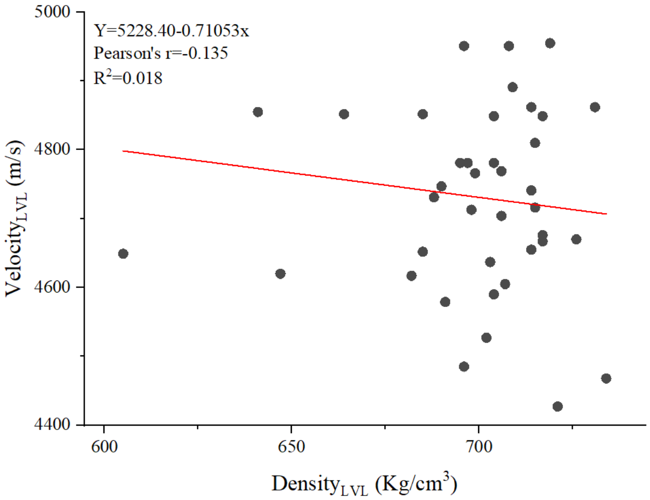

Figure 11. Relationship between density and velocity of the LVL.

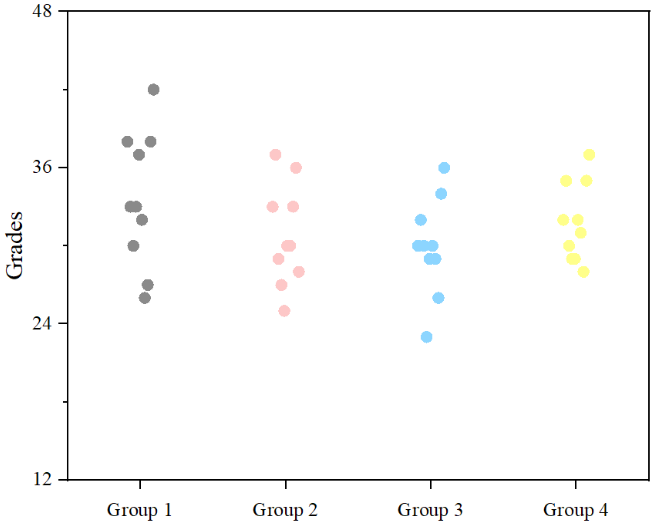

Figure 12. Distribution of LVL billet grading value based on veneer composition.

While the grading score provides an overview of the veneer quality composition in the LVL billets, it was also important to examine the effect of LVL grade number on the mechanical properties of the final product. A regression analysis was conducted between the LVL grade number and its associated dynamic modulus of elasticity, using OriginPro software, as shown in Figure 13.

The regression analysis showed a weak correlation between the two parameters, with a Pearson's r of -0.268 and a coefficient of determination of 0.07, suggesting that only 7% of the variation of the MOE_{dLVL} can be explained by the presence of defects, indicating that the grading alone does not strongly predict the MOE_{dLVL}.

The presence of the weak correlation was unexpected, as higher-grade veneers were assumed to enhance the mechanical properties of the LVL billets. This suggests that other factors, such as veneer orientation, adhesive type, and natural variabil-

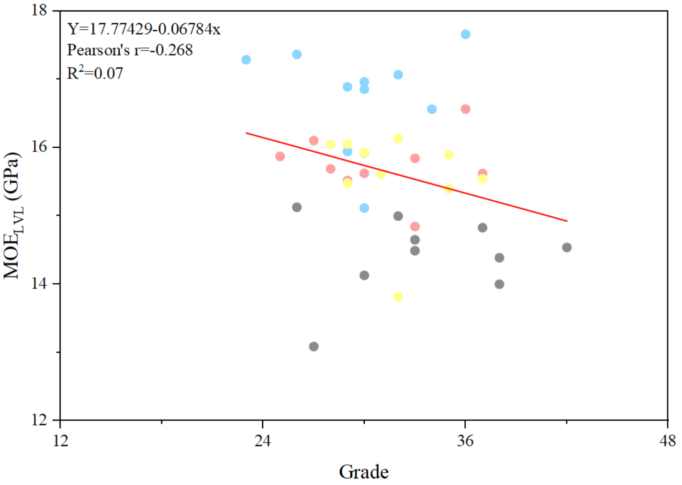

Figure 13. Relationship between LVL grading score and its associated MOE_{dLVL}.

ity in wood properties, may have influenced the mechanical performance of the LVL billets.

According to Bucur (2006), in addition to the natural imperfections, cracks and fiber deviation can also affect the stiffness of wood material (Bucur 2006). Similarly, studies by Kollmann (1951) and Eberhardsteiner (1995) have shown that fiber and microfibril angles also play a critical role in determining the stiffness and strength of wood.

Conclusion

The study investigates the relationship between the mechanical properties of individual veneers and the overall structural performance of LVL billets using two nondestructive evaluation tools—the Fakopp Microsecond Timer and the Hitman HM200. The veneers were classified by dynamic MOE into low, medium, high, and mixed groups.

The key findings are summarized as follows:

1. A strong correlation was found between MOE of veneers (MOE_{dLVL}) and the resulting LVL billets ($MOE_{dVeneer}$), with a correlation coefficient (r) of 0.85 and an R^2 value of 0.73. This indicates that veneer properties significantly influence LVL performance.

2. MOE values obtained from the Fakopp and the Hitman HM200 devices showed a strong correlation (r = 0.93, R^2 = 0.86), confirming the reliability and consistency of both measurement approaches.

3. The LVL billets exhibited a noticeable reduction in MOE compared to their source veneers, ranging from 12.5% to 24.47%, with the greatest reduction observed in high-grade veneer group.

4. Within each group, higher veneer MOE corresponded to higher LVL MOE, indicating that higher-quality veneers resulted in stronger LVL billets. Conversely, lower-quality veneers resulted in weaker LVL billets.

5. The mixed group, where high-grade veneers were placed on the outer layers and medium- and low-grade veneers formed the core, produced MOE values (19 GPa for veneer, 15.58 GPa for LVL) comparable to the medium-grade group (19 GPa for veneer, 15.75 GPa for LV), suggesting an efficient use of mixed-quality veneers.

6. A weak correlation was observed between the grading score and the dynamic modulus of elasticity of the LVL (r = -0.26, R^2 = 0.07), indicating that grading score alone is not a reliable predictor of LVL stiffness.

The findings of this study provide practical insights into veneer selection and layup strategies to enhance LVL performance and improve wood utilization efficiency.

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