Physical and Mechanical Properties of Laminated Timbers Used In the Construction and Furniture Industry

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Some physical and mechanical properties of laminated timbers used in wooden construction and furniture industry were examined. Polyurethane (PU) glue was used in the production of laminates with 5 layers. The surface layers in each laminated timber (Glulam) were from the same wood type, and the core layers were from willow wood. The laminated timbers whose outer layers were made of willow (*Salix alba* L.), yellow pine (*Pinus sylvestris* L.), and ash (*Fraxinus* L.) wood had an air-dry density value of 0.60 g/cm^3 in laminated timber with the highest ash wood surface. The pressure resistance parallel to the fibers was determined in the surface layer ash wood with 48.6 N/mm^2. It was found that the static bending resistance was 91.1 N/mm^2 in laminated timber with a surface layer of ash wood, and the modulus of elasticity value in bending was 10040 N/mm^2 in laminated timber with the highest ash wood surface. Thus, it has been seen in the study that improvements in physical and mechanical properties were achieved, especially as a result of combining willow wood (having fast growth potential and low density) with high-density wood types. According to the results of the study, it is recommended to carry out the necessary studies to increase the physical and mechanical properties of low-density wood types by laminating them with high-density wood types.

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INTRODUCTION

Engineered wood-based industrial products such as glued laminated timber (Glulam), laminated veneer lumber (LVL), parallel strand lumber (PSL), and LSL laminated strand lumber (LSL) were designed for use in wood structural applications. Such products are obtained by gluing multiple layers with various adhesives under the influence of the lamination technique (Mengeloğlu and Kurt 2004). By producing engineered wood-based materials, the negative properties (sensitivity to water and humidity) of natural wood materials are minimized, defects (cracks, knots, intercalation and insect and fungal damage) that would reduce their aesthetic value are eliminated, and mechanical properties are improved (Söğütlü and Döngel 2007; Rowell 2012; Sandberg *et al*. 2017; Dong *et al*. 2020). Glulam has gained popularity in structural applications in the USA, Europe, and Asian countries (Kremer and Symmons 2015; Lall *et al*. 2019). Despite its higher cost, glulam is preferred due to its low density, lower transportation costs, and ease of installation as a semi-finished product, as well as its contributions such as shortening construction times (Gustavsson *et al*. 2006) and reducing carbon footprint (D'Amico *et al*. 2021).

Laminated timber, which has a widespread use in the furniture and construction sector, is an engineering product obtained by gluing two or more lamellas on top of each other with various glues so that the fiber directions are perpendicular or parallel to each other (Karaman and Yıldırım 2018). The structure of the wood material, press pressure, pressing time, and the glue used are important relative to the adhesion strength of produced laminated timber (Bobat 1994). One of the most important factors in the formation of mechanical strength in laminated timber after the effect of wood species is the glue factor (Uysal *et al*. 2005). According to the general opinion, the use of glue between the layers has an increasing effect on the mechanical strength of laminated timber, but in reality, an excessive layer of glue causes a decrease in mechanical strength as it negatively affects the permeability of the surfaces (de Oliveira *et al*. 2020). In addition, another factor to be considered for lamination is that the pressing pressure should be adjusted according to the softwood species and should be between 0.6 and 1 N/mm^2 (Dilik 1997). According to Kuzman *et al*. (2010), the lamellae in laminated timbers become more stable, the anisotropic structure of the wood material, which is a unique feature of the wood material, becomes more stable, internal stresses decrease, mechanical strength, and the material becomes more resistant to effects such as water, moisture, and temperature.

Meeting the increasing demand for forest products as a result of the world population growth is only possible through the plantation of wood species that can grow rapidly (Göker and Dündar 1999). However, due to the rapid growth of these wood species; they have insufficient quality characteristics such as low density, less stability, and low strength. Therefore, in order to minimize these deficiencies, it is possible to use wood species with low resistance and quality in the intermediate layers in lamination and wood species with high density and strength properties in the surface layers (Dündar *et al*. 2016).

In this study, it was aimed that willow wood, which has a low density and has a fairly low economic value compared to other wood types, but also has a rapid growth potential, can be laminated with wood types with high density and high values in terms of mechanical strength, so that industrial timber production with sufficient physical and mechanical strength can be achieved.

EXPERIMENTAL

Materials

Willow (*Salix alba* L.) with density of 0.45 g/cm^3, ash (*Fraxinus* L.) with density of 0.70 g/cm^3, and yellow pine (*Pinus sylvestris* L.) with density of 0.59 g/cm^3 were used in the production of laminated timbers in this study. The criteria for selection of wood pieces was smooth fibers, knotless, crack-free, reaction wood, absence of rot, insect, and fungal damage, and first class properties. Wood was selected randomly from the timber trading organizations in Erzurum, Republic of Turkey.

Production of Glued Laminated Samples

The wood lamellas forming the laminated timbers, with net dimensions of (75 x 4 x 600) mm^3, were conditioned under 20 °C temperature and 65% relative humidity conditions in an air conditioning room until they reached constant weight. The conditioned lamellas were glued on top of each other with the fiber directions parallel to each other based on the 5-layer arrangement as shown in Fig. 1, and test specimens with dimensions of (75 x 20 x 600) mm^3 were obtained. Polyurethane (PUR) glue was used to produce the specimens and 180 to 220 g per m^2 was applied and pressed at 20 °C for 60 min with a pressure of 0.8 N/mm^2. The specimens were then cut on a circular sawing machine according to the dimensions specified in the standards for these experiments.

Fig. 1. Arrangements of lamellas in laminated timber: 1-willow wood; 2- willow, ash or yellow pine wood.

Air Dry Density

Air dry density values of laminated timber produced from different wood species were determined according to TS 5497 EN 408 (2006). According to this standard, a total of 30 specimens, 10 specimens of (30 x 20 x 20) mm^3, were prepared from each combination group. The specimens were conditioned at a temperature of 20 ± 2 °C and 65% relative humidity until they reached constant weight between two the 6 h intervals weighting.

Strength of Compression Parallel to the Grain

The compression test parallel to the grain was carried out (Fig. 2) according to ISO 13061-17 (2017) after the test specimens with dimensions of (30 x 20 x 20) mm^3 and 10 specimens for each test group were conditioned under 20 ± 2 °C temperature and 65% relative humidity conditions. In the experiments, the loading rate was applied as 4 mm/min. During the experiments, the maximum force ($F_{\max}$) was recorded (N), and the compressive resistance parallel to the fibers (σB) of each test sample was calculated by Eq. 1,

$$\sigma_B = F_{max}/A \tag{1}$$

where σ_B is compressive strength (N/mm^2), and A is sample cross-sectional area (mm^2).

Fig. 2. Pressure testing of laminated timbers

Determination of Static Bending Strength and Modulus of Elasticity in Bending

An Instron 5969 branded universal testing machine in the test laboratory of Gazi University, Faculty of Technology, Department of Woodworking Industrial Engineering was used to determine of static bending strength and modulus of elasticity in bending of laminated timbers conditioned at 20 ± 2 °C temperature and 65% relative humidity conditions. In static bending strength tests, the principles specified in TS ISO 13061-3 (2021) for bending strength and TS ISO 13061-4 (2021) for modulus of elasticity in bending for solid wood materials were followed. The test specimens (Fig. 3) were (360 x 20 x 20) mm^3. Thirty experiments were performed in total, 5 perpendicular to the glue line and 5 parallel to the glue line and in 3-point bending experiment, with a force application of 10 mm per minute.

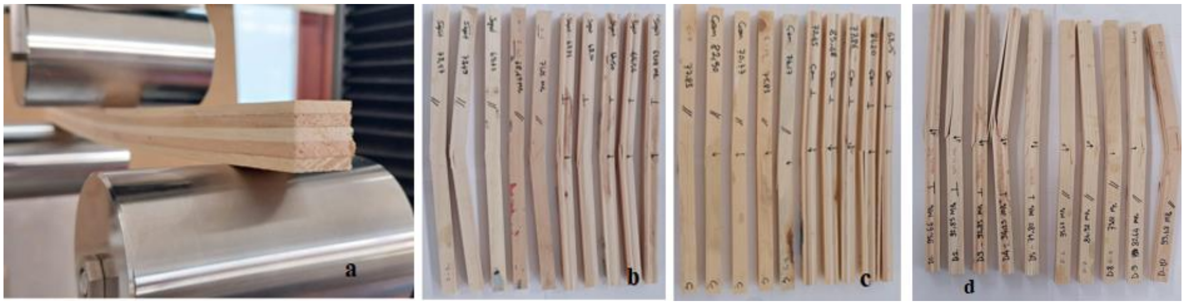

Fig. 3. Determination of static bending strength and modulus of elasticity in bending; (a) Static bending test setup, (b, c, and d) Specimens after static bending test

Data Analysis

SPSS 26 and MSTAT-C programs were preferred to analyze the data obtained by experimental methods. With these programs, multi-way analysis of variance (MANOVA) and multiple comparisons were performed based on 95% confidence index.

RESULTS AND DISCUSSION

Air Dry Density

Statistical data on the air-dry density values of laminated timber at the time of reaching constant mass in the weight measurements made at 6-h intervals under 20 ± 2 °C temperature and 65% relative humidity conditions of the test specimens prepared according to TS 5497 EN 408 are given in Table 1.

Table 1. Statistical Data on Air Dry Density (g/cm^3) Values of Laminated Timber

Surface Layer	N	X_{min}	X_{max}	X_{mean}	Std. Dev.
Willow	10	0.49	0.52	0.50^{*C}	0.011
Ash	10	0.58	0.64	0.60^{*A}	0.021
Yellow pine	10	0.49	0.54	0.52^{*B}	0.018
LSD: 0.009 g/cm^3 ; * : Homogeneity groups					

The air dry density values of laminated timbers were different from each other. To determine whether the air dry density values were significantly different from each other, multi-way analysis of variance was performed. The results of multi-way (MANOVA) analysis of variance for air dry density values of laminated timbers are given in Table 2.

Table 2. Multi-way Analysis of Variance Results for Air Dry Density Values of Laminated Timber

Source	Sum of Squares	df	Mean square	F	Sig. ($p<0.05$)	Partial Eta^2
Surface Layer	0.061	2	0.031	105.565	0.000	0.89
Error	0.008	27	0.0001			
Total	8.825	30				
Corrected Total	0.069	29				

The effect of the wood type used in the surface layer of the laminated timbers on the air dry density values of the laminated timbers was significant ($p<0.05$; F: 105.565), and the effect level was high (89%). When only willow wood was used in the inner layer, it was not included in the analysis of variance. Duncan's test was performed to determine the difference between the groups belonging to the surface layer factor, which had a significant effect on the air dry density values of laminated timber, and the homogeneity values between the groups are given in Table 1.

According to the results of the Duncan test in Table 1, the density values of laminated timbers were significantly different from each other depending on the wood species used in the outer layer. The laminated timber with the highest density value was 0.60 g/cm^3 in the laminated timber with ash surface. This result can be attributed to the high density value of ash wood.

In previous studies, it was determined that the density of the outer knot wood grown in Turkey was between 0.450 to 0.860 g/cm^3 (Şahin and Güler 2015), and the density of laminated timber produced from yellow pine wood was 0.537 g/cm^3 (Kurt *et al.* 2003). However, no lamination study on willow wood was found. Therefore, the air dry density values of ash and yellowwood used in this study were similar to these values.

Strength of Compression Parallel to the Grain

Statistical data on the values of compressive strength parallel to the fibers of laminated timber produced from different wood species are given in Table 3.

Table 3. Statistical Data on the Compressive Strength Parallel to the Fibers (N/mm^2) of Laminated Timber Produced from Different Wood Species

Surface Layer	N	Xmin	Xmax	Xmean	Std. Dev.
Willow	10	37.71	41.37	39.10^{*C}	1.30
Ash	10	42.90	53.90	48.62^{*A}	4.01
Yellow pine	10	40.88	48.92	44.22^{*B}	2.59
LSD: 2.10 N/mm^2 ; *: Homogeneity groups					

The compressive strengths of laminated timber with different surface layers were different from each other in the direction parallel to the fibers. The highest compressive resistance parallel to the fibers was 46.6 N/mm^2 in the laminated timber with ash surface. The lowest was obtained in laminated timber with willow wood surface with 39.1 N/mm^2.

Multidirectional analysis of variance was performed to determine whether the differences in the compressive strengths of laminated timbers parallel to the fibers were significantly different.

The results of multi-way (MANOVA) analysis of variance for the pressure parallel to the fibers of laminated timbers are given in Table 4. The effect of the wood species used in the surface layer of laminated timbers on the compressive strength parallel to the fibers was significant ($p<0.05$; F:29.638) and the level of effect was high (68.7%). Duncan's test was performed to determine the difference between the groups belonging to the outer layer factor, which had a significant effect on the parallel pressure values of laminated timber.

Table 4. Results of Multi-Way Analysis of Variance for Pressure Values Parallel to Fibers of Laminated Timber

Source	Sum of Squares	df	Mean square	F	Sig. ($p<0.05$)	Partial Eta^2
Surface Layer	453.826	2	226.913	29.638	0.000	0.687
Error	206.718	27	7.656			
Total	58693.034	30				
Corrected Total	660.544	29				

The homogeneity values between the groups are given in Table 3. The compressive strength parallel to the fibers of the laminated timbers were significantly different from each other depending on the wood species used in the surface layer. The highest fiber parallel compressive strength was found to be in the laminated timber with ash surface (48.6 N/mm^2). The values of resistance parallel to the fibers in the timbers subjected to the experiments are parallel to the densities of the wood species used.

In previous studies, the compressive strength of yellow pine wood parallel to the fibers was found to be 42.6 N/mm^2 (Özçiftçi and Batan 2009), and the compressive strength of laminated timber produced from yellow pine parallel to the fibers was 42.13 N/mm^2 (Perçin *et al*. 2009). The compressive strength of willow wood parallel to the fibers is 33.4 N/mm^2 (Bozkurt and Göker 2014), but no study was found on the compressive strength of laminated timber produced from willow wood. The compressive strength parallel to the fibers in ash laminated with black poplar is 56.4 N/mm^2 (Keskin and Atar 2010), while the average compressive strength parallel to the fibers of ash wood grown in the Black Sea region was 50.0 N/mm^2 (Hızal and Erdin 2020). Therefore, in this study, both lamination application and laminating different wood species with willow wood provided a significant improvement in the compressive strength parallel to the fibers.

Determination of Static Bending Strength

The static bending strength of the laminated timbers given in Table 5 were different from each other. The static bending strength of laminated timbers with surface layers of ash and pine wood was higher than static bending strength of laminated timbers with surface layers of willow wood.

A multi-way analysis of variance was performed to determine the significance levels of the differences between static bending strength of the laminated timbers obtained for all combinations in this study within 5% margin of error; the results are given in Table 6. Only the effect of the surface layer factor was significant (F: 26.461; $P<0.05$) among the factors included in the production of laminated timber obtained in different combinations. The effects of the force direction factor, whose effect on static bending strength was measured, and the double interaction of the surface layer and force direction factors on static bending strength of laminated timber produced from different wood species were not significant. The effect level of the surface layer factor, which has a significant effect on static bending strength, was found to be at a high level (68.8%).

Table 5. Statistical Data on Static Bending Strength (N/mm^2) of Laminated Timber Produced from Different Wood Species

Surface Layer	Force Direction (Glue line)	*N*	X_{min}	X_{max}	X_{mean}	Std. Dev.
Willow	Perpendicular	5	64.56	68.50	66.91	1.5
Ash	Perpendicular	5	79.80	95.66	91.09	6.42
Yellow pine	Perpendicular	5	63.15	85.48	76.03	8.63
Willow	Parallel	5	68.45	73.57	71.28	2.29
Ash	Parallel	5	75.53	99.68	87.68	9.85
Yellow pine	Parallel	5	70.70	82.90	78.42	4.52

Table 6. Multiple Variance Analysis of Static Bending Strength of Laminated Timber

Source	Sum of Squares	df	Mean square	F	Sig. ($p<0.05$)	Partial Eta^2
Surface Layer	2121.358	2	1060.679	26.461	0.000	0.688
Force Direction	1.220	1	1.220	0.030	0.863	0.001
Surface Layer * Force Direction	75.621	2	37.810	0.943	0.403	0.073
Error	962.022	24	40.084			
Total	186681.551	30				
Corrected Total	3160.221	29				

According to the variance analysis table, Duncan test was performed to determine the homogeneity between the groups belonging to the surface layer factor, which was found to have a significant effect on static bending strength of laminated timber, and the results are given in Table 7. There was a significant (95%) difference between the wood species used in the formation of the surface layer factor, which was found to have a significant effect on the static bending resistance of laminated timber. According to the results of the analysis, it can be said that static bending strength resistance of the laminated timber whose surface layer is made of ash wood was higher than the laminated timber whose surface layers are produced from other wood species; and it can be said that this level of resistance was realized depending on the density value of ash wood species.

Table 7. Homogeneity Groups of Surface Layer with Significant Effect on Static Bending Strength

Surface Layer	$\bar{X}$ (N/mm^2)	HG
Willow	69.10	C
Yellow pine	76.16	B
Ash	89.38	A
LSD: 5.79 N/mm^2 ; HG: Homogeneity groups		

In the literature, the bending strength of 3-layer yellow pine laminated timber with a laminated thickness of 30 mm was reported as 61.2 N/mm^2 (Güler and Subaşı 2012), and in another study, bending strength of yellow pine laminated timber perpendicular to the glue line was 79.7 N/mm^2, while bending strength parallel to the glue line was 73.1 N/mm^2 (Kasal *et al*. 2010) was determined. In another study, the static bending strength of 5-layer laminated timbers produced only from ash wood was 97.8 N/mm^2 (Keskin and Atar 2010). The bending strength of laminated timbers obtained from beech, oak, yellow pine and poplar woods in different combinations ranged from 76.1 to 107.5 N/mm^2 (Keskin and Togay 2003; Keskin 2004). In this study, the static bending strength of the laminated timbers obtained by using different wood species were close to the results of previous similar studies. Willow wood, which has weak mechanical strength, used in the yellow pine/willow and ash/willow combinations in this study, did not cause a significant decrease in the bending strengths of the laminated timbers.

The Modulus of Elasticity in Bending

The statistical values of the modulus of elasticity in bending of 5 layer laminated timbers produced from different types of wood are given in Table 8. The elasticity modulus values in bending of laminated timber made of different wood species were found to be different from each other. Notably, the elasticity modulus value of laminated timber produced from the surface layer of ash wood was higher in bending perpendicular and parallel to the glue line than other wood species.

Table 8. Statistical Data on the Modulus of Elasticity in Bending (N/mm^2) Values for Laminated Timber Produced from Different Wood Species

Surface Layer	Force Direction (Glue line)	N	Xmin	Xmax	Xmean	Std. Dev.
Willow	Perpendicular	5	6179.50	6869.77	6577.41	255.03
Ash	Perpendicular	5	8985.59	12001.35	10040.38	1155.43
Yellow pine	Perpendicular	5	7116.68	9584.00	8174.90	1071.09
Willow	Parallel	5	6677.81	7112.46	6877.55	186.19
Ash	Parallel	5	7137.21	10402.32	8658.24	1439.09
Yellow pine	Parallel	5	7157.18	9158.45	7960.84	776.24

A multifactorial variance analysis was conducted to determine whether the differences in the modulus of elasticity values of laminated timber in all combinations were significant within a 5% margin of error; the results are presented in Table 9. The effects of using different wood species in the surface layer of laminated timber, produced with combinations of different wood types, on the elastic modulus values in bending of laminated timber were significant (F: 19.62; $P<0.05$). The effect level of the surface layer, which was identified as significant, was at a high level (62.1%).

The Duncan test was conducted to determine the homogeneity groups among the wood species used in the surface layer, where the effect was found to be significant according to the analysis of variance table; the results are presented in Table 10. The elasticity modulus values of laminated veneer lumber produced from different wood species were statistically significantly different from each other depending on the wood species used in the surface layer. The elasticity modulus value of laminated veneer lumber produced from the surface layer of ash wood is higher compared to other wood species (Yellow pine and willow). This observed value is dependent on the density of ash wood.

Table 9. The Multifactorial Variance Analysis of the Elastic Modulus in Bending of Laminated Timber

Source	Sum of Squares	df	Mean square	F	Sig. ($p<0.05$)	Partial Eta^2
Surface Layer	34375883.91	2	17187941.95	19.62	0.000	0.621
Force Direction	1399822.56	1	1399822.56	1.60	0.218	0.062
Surface Layer * Force Direction	3715726.96	2	1857863.48	2.12	0.142	0.150
Error	21022011.77	24	875917.16			
Total	2003728317.36	30				
Corrected Total	60513445.20	29				

Table 10. Homogeneity Groups of Surface Layer with Significant Effect on Modulus of Elasticity in Bending

Surface Layer	$\bar{X}$ (N/mm^2)	HG
Willow	6627.48	C
Yellow pine	8067.87	B
Ash	9349.31	A
LSD: 856.0 N/mm^2 ; HG: Homogeneity groups		

In the studies conducted, it has been determined that the bending elasticity modulus values in laminated pine lumber are 10400 N/mm² (Kurt *et al*. 2003) and 9840 N/mm². Additionally, the bending elasticity modulus resistance has been determined as 9500 N/mm² by using poplar wood in the middle layers (Dündar *et al*. 2016). The bending elasticity modulus value in ash wood is 13.300 N/mm², while it has been determined that the bending elasticity modulus value in laminated lumber created with pine wood is 11000 N/mm² (İlçe 2018). Therefore, the results regarding the bending elasticity modulus values obtained from similar studies conducted previously are in similar proportions to the results of this study. When using ash and yellow pine woods in the surface layers of laminated timbers whose core layers consist of willow wood, the laminated timber obtained provided an increase in mechanical properties such as static bending strength, modulus of elasticity in bending, and compressive strength parallel to the grain. Based on the results of this study, it is recommended that willow wood, which has weak mechanical properties, should be laminated with different wood species with stronger mechanical properties and different glues.

CONCLUSIONS

1. The use of yellow pine wood in the surface layers of laminated timber provided a 4% increase in density, while the use of ash wood provided a 20% increase. These increases in the density values of laminated timber were found to be statistically significant.
2. Yellow pine wood used in the surface layers of laminated timber provided a 13% increase in compressive strength parallel to the grain, while ash wood showed a 24% increase.
3. Yellow pine wood used in the surface layers of laminated timber provided a 10% increase in static bending strength, while ash wood gave a 29% increase. In terms of

elasticity modulus in bending, yellow pine wood showed a 21.7% increase, whereas ash wood demonstrated a 41% increase.

4. The direction of force in the bending test of laminated timber, whether perpendicular or parallel to the glue line, did not have a statistically significant effect.

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