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Effect of Layer Arrangement on Expansion, Bending Strength and Modulus of Elasticity of Solid Wood and Laminated Veneer Lumber (LVL) Produced from Pine and Poplar

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ABSTRACT

In this study, it was aimed to determine whether or not the layer organizations were influential on the expansion in volume after keeping in water for 2 hours, on the bending strength and modulus of elasticity values of laminated veneer lumber (LVL). Austrian pine (*Pinus nigra*) (A) and Lombardy poplar (*Populus nigra*) (B) veneers with thicknesses of 3 mm were used for the production of laminated veneer lumber. A total of 110 test specimens with 8 different layer organizations were prepared by using polyvinyl acetate based (PVAc-D4) adhesive. Solid Austrian pine and Lombardy poplar woods in the same dimensions were used as control specimens. At the end of the tests; the bending strength and modulus of elasticity values of all the LVLs with different combinations were found to be higher compared to the control specimens. The strength characteristics of the LVL increase as the percentage of Austrian pine increases.

Key Words**:** Lamination, Laminated Veneer Lumber (LVL), Bending Strength, Modulus of Elasticity, PVAc Adhesive.

1. INTRODUCTION

Wood as a material, besides the known positive characteristics, also have negative attributes, such as structural quality differences, changing dimensions, warping and extractive concentration due to heteregoneous structural characteristics. Wood is restructured as composite with different physical, chemical and mechanical processes in order to eliminate these shortcomings. New wood-based materials for different purposes of use are manufactured to improve the strength characteristics and to make use of them more economically. Lamination is one of these structures. In the lamination method, veneers with the same or different thicknesses are obtained from the same or different wood types and are bonded one on top of the other with different adhesive types. The fiber directions of the veneers are parallel to each other.

The following advantages are provided with the laminated wooden materials:

i) It is possible to produce stronger wooden materials having different structural characteristics from solid woods with the use of adhesives having different characteristics.

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ii) Composite materials with developed characteristics can be produced by using materials such as metal, plastic and textiles in different layers.

iii) It is possible to produce wooden materials in desired dimensions different from the available commercial lumber standards.

iv) In lamination, using different wood types can produce wooden structural elements having different aesthetic appearances.

v) Low quality materials can be used in the inner portion of laminated elements.

vi) Long wooden structural materials can be produced from short pieces.

vii) Structural elements with large curves can be produced.

The physical, mechanical, thermal, acoustic and other characteristics of the laminated materials produced in accordance with the principles listed above change according to the wood species used along with the factors such as the general characteristics of the layer materials, the composition of wood types, the type of adhesive, layer thicknesses, etc.

The bending strength of solid beams supported with laminated layers is 10 % higher than those not supported with laminated layers. The bending strength of first grade beams supported with 3 mm veneers is 6 % higher than the second and third grade beams supported with 2.2 mm veneers. The quality of wood used in the lamination in laminated wooden materials affects the bending strength. The bending strength of beams produced from first grade veneers is 6 % higher compared to those produced from second and third grade veneers [1]. In a study aimed at its usability as a carrying system element in structures of the lumber obtained by lamination from the small diameter and short fir wood, it was determined that structural elements with higher quality characteristics could be produced with lamination method, by using low quality woods with lower costs [2]. The number of knots, the diameter of the knots and the distance between knots in the laminated layers affect the bending strength of the materials produced; hence the distance between two knots should be at least 9 cm [3]. The laminated layer width, in beams laminated with 4 layers and 15 and 20 cm layer widths from fir and Southern pine having minimum quality characteristics, is not found to be influential on bending strength [4]. In fir specimens having different layer thicknesses and different veneer quality grades, the width of the layers is not found to be influential on bending strength and modulus of elasticity. As the thicknesses of the laminated layers increase, the bending strength decreases. Whereas the modulus of elasticity is not affected by layer thickness [5]. Modulus of elasticity varies according to the type of wood [5, 6, 7, 8]. The type of wood and the type of adhesive affect the strength characteristics of the laminated materials [4, 6, 7, 8, 9, 10, 11, 12, 13].

Different materials are also used together with wood to improve the structural characteristics of the materials obtained in the production of laminated wooden materials. Graphite-epoxy and polyester-glass are used to improve the hardness and strength characteristics of wood. In the mixed laminations made with fir, the graphite-epoxy laminations have better hardness values compared to the polyester-glass laminations and in the bending test, the polyester-glass laminations give better results compared to the graphite-epoxy laminations [14]. In the determination of the resistance point against cracks that could arise due to tensions in the wooden laminated beams in different forms, the cracks advance slower in the laminated wooden beams strengthened with glass fibers compared to the beams which have not been reinforced. The reinforcement decreases the tension in the cracks and assumes a kind of crack-stopper function [15].

Lombardy poplar is a softwood species, which is grown extensively, especially as a garden tree. It has low density and low strength values. These characteristics of this wood restrict its areas of use and prevents its use as a structural material. In this study, it was aimed to determine some physical characteristics of the materials produced with the lamination of Austrian pine, which is used extensively as a structural material, and Lombardy poplar, and to examine the opportunities of using them together as a structural material.

It was aimed to determine whether or not the layer organizations were influential on the expansion in volume after keeping in water for 2 hours, on the bending strength and on the modulus of elasticity values.

2. MATERIALS AND METHOD

2.1. Wood materials

Austrian pine (*Pinus nigra*) and Lombardy poplar (*Populus nigra*) woods were used as wood materials. Care was taken to make sure that the materials taken for specimens had regular grain directions did not have knots, did not have changes in color, displayed normal growths, did not contain reaction wood and have not been harmed by fungus and insects.

2.2. Adhesive

The PVAc-D4 type adhesive was used in bonding of the layers on top of each other for forming the specimens. The PVAc-D4 used in the study is a single-component adhesive and has a D3 bonding quality according to DIN EN 204 [16]. Its density is 1.12 g/cm^3, its viscosity is 13 000 ± 2 000 mPa.s at 20 °C and the pH value is 3. Klebit Turbo-Hardener 303.5 at the ratio of 5 % was used as hardener.

2.3. Preparation of the specimens

The Austrian pine and Lombardy poplar lumbers obtained from the logs were subjected to drying in automatic drying kiln until they reached a moisture content (MC) of 12 % and the dried lumber was stacked in a natural environment. Subsequently, stock laminations having rough dimensions of 50x50x450 mm (thickness x width x length) were cut from this lumber. These laminations were sanded equally on both surfaces in the oscillating wide belt sanding machine with a 60-grit sand paper to produce laminations with thicknesses of 3 mm. The laminations were kept in a climatization chamber having a relative humidity of 65 ± 5 % and a temperature of 20 ± 2°C until they reached a constant weight 12 % MC with the objective of homogenizing the moisture in volume prior to the sanding process. The principles in the TS EN 310 [17] standard were taken into consideration in the determination of the dimensions of the laminations and in the preparation of the specimens. The PVAc-D4 adhesive was applied on one side of the laminations uniformly as 160 g/m², according to the recommendations of the manufacturer. The glued laminations were brought one on top of the other in 7 layers and in 8 different compositions in the form of AABABAA, BABABAB, ABABABA, ABBABBA, AABBBAA, ABBBBBA, AAAAAAA and BBBBBBB (A:Austrian pine and B:Lombardy poplar) and were pressed for 15 minutes at a pressure of 1 N/mm² in a press at 20 ± 1°C. The stock pieces coming out of the press were transformed into specific gravity test specimens with the finished dimensions of 20 x 20 x 30 mm, and into bending strength and modulus of elasticity specimens with the finished dimensions of 20 x 20 x 360 mm. In this manner, the pressing continued to provide a total of 88 specimens with 11 for each composition. A total of 22 each Austrian pine and Lombardy poplar solid test specimens in the same dimensions were prepared as control specimens.

The test specimens were kept in a climatization chamber having a relative humidity of 65 ± 5 % and a temperature of 20 ± 2 °C until they reached a constant weight (and until they reached a moisture content of 12 %) with the objective of homogenizing the moisture in volume prior to the tests. Subsequently, the specimens were insulated to prevent a loss of moisture and were kept until the tests were made.

2.3. Method

2.3.1. Air dry density and expansion in volume

The air dry density at moisture content of 12 % was calculated according to the principles in the TS 2472 [18].

The test pieces were prepared in the dimensions of 20 x 20 x 20 mm within the scope of the expansion in volume test and were kept in water for a period of 2 hours. The amount of expansion in volume was calculated according to the principles of TS 4086 [19].

2.3.3. Bending strength (MOR) and modulus of elasticity (MOE)

The tests were carried out on computer-controlled 1000 kg capacity TIRA testing machine. The specimens were placed in the testing machine as shown in Figure 1. A loading was made in a manner to break the specimen in 90 ± 0.5 seconds with a fixed speed and the load (F_{max}) at the moment of breaking was determined and recorded. The values obtained were placed in formula 3 and the bending strengths were determined.

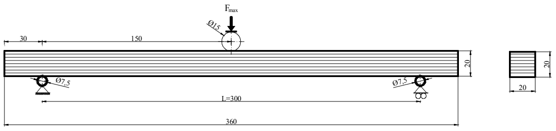

Figure 1. The test mechanism for bending strength and modulus of elasticity.

$$\sigma_E = \frac{3.F_{max}.l}{2.b.h^2} \qquad (1)$$

where; σ_E= bending strength (N/mm²), F_{max} = breaking load (N), l = space between the supports (mm), b = width of the specimens (mm), h = height of the specimens (mm)

The tests for the determination of modulus of elasticity were made according to the principles of TS EN 310 [17]. The following equation was used for the determination of the modulus of elasticity with the help of the applied force difference (ΔF) in the elastic deformation region and the difference (Δf) of the bending amounts in the example:

$$E = \frac{\Delta F.l^3}{4.b.h^3.\Delta f} \qquad (2)$$

where; (E) = modulus of elasticity (N/mm²),

(l) = distance between the supports (mm),

(b) and (h) = width and height of the specimens (mm)

2.3.4. Evaluation of data

The F test was used to determine the effect on the density, bending strength and modulus of elasticity of the solid materials and the 8 different layer combinations of the two different types of wood used in the study. In case there was a significant difference among the groups, then a comparison was made with the Duncan test at a confidence level of α=0.05. The SPSS package program was used in calculations of Analysis of Variance (ANOVA), average, standard deviation, standard error, and minimum and maximum values.

3. RESULTS AND DISCUSSION

The average bending strengths, modulus of elasticity, air-dry density and the expansion in volume values in water for 2 hours of the laminated wooden materials produced with the lamination of Austrian pine and Lombardy poplar are given in Table 1. The test moisture content is accepted as air dry (12 % MC).

Table 1. The bending strengths, modulus of elasticity, the expansion in volume in water for 2 hours and the air dry density values of the laminated materials produced with different layer organizations from Austrian pine (A) and Lombardy poplar (B).

Material	**MOR (N/mm^2)**	**S**	**MOE (N/mm^2)**	**S**	**Expansion in Volume (%)**	**S**	**Density (gr/cm^3)**
AABABAA	77.97*	7.58	8,225.73	723.27	12.16	3.93	0.51
BABABAB	67.11	9.21	6,316.27	521.62	**10.47**	3.29	0.47
ABABABA	74.76	4.49	7,412.33	618.83	13.56	2.03	0.49
ABBABBA	62.27	16.23	9,804.64	870.88	12.09	2.32	0.48
AABBBAA	75.06	7.02	8,468.09	714.23	11.40	3.24	0.49
ABBBBBA	52.01	19.86	7,830.55	828.69	17.77	5.64	0.48
AAAAAAA	**83.98**	13.46	8,326.36	680.10	11.73	1.89	**0.55**
BBBBBBB	57.16	4.28	5,667.91	630.18	14.45	6.71	0.41
Solid Austrian pine	78.83	17.38	8,147.82	1784.07	12.76	5.07	0.50
Solid Lombardy poplar	55.33	16.83	5,810.36	1791.52	11.19	2.93	0.31

As it can be seen from an examination of the table, the highest bending strength (83.98 N/mm^2) was obtained with the AAAAAAA layer organization formed with the lamination of Austrian pine. It was followed by solid Austrian pine at 78.83 N/mm^2 and the AABABAA layer organization, which had the highest percentage of Austrian pine. The lowest bending strength value (52.01 N/mm^2) appeared in the ABBBBBA layer organization, which had the highest percentage of Lombardy poplar. Whereas, solid Lombardy poplar has the second lowest bending strength value (Table 1).

The highest modulus of elasticity value (9,804.64 N/mm^2) was obtained in the specimens produced with the ABBABBA layer organization. It was followed by specimens with the AABBBAA layer organization with a modulus of elasticity value of 8,468.09 N/mm^2 and the specimens with the AAAAAAA layer organization with a modulus of elasticity value of 8,326.36 N/mm^2. The lowest modulus of elasticity value (5,810.36 N/mm^2) was obtained in the solid Lombardy poplar specimens (Table 1).

The highest expansion in volume (17.77 %) at the end of being kept in water for 2 hours was obtained in the specimens with the ABBBBBA layer organization. This was followed by the specimens with the BBBBBBB layer organization at 14.45 %. The lowest increase in volume (10.47 %) appeared in the specimens with the BABABAB layer organization.

As it was expected, the lamination of different wood types caused an increase in the specific gravities compared to solid materials. At the end of laminating different layer structures of Austrian pine and Lombardy poplar, the highest air dry density (0.55 gr/cm^3) emerged in the specimens having the AAAAAAA layer organization in which all of the layers were Austrian pine. The lowest oven-dry density (0.41 gr/cm^3) appeared in the specimens having the BBBBBBB layer organization in which all of the layers were Lombardy poplar. Due to the fact that Austrian pine has a higher density, an increase in the percentage of Austrian pine in the lamination causes an increase in the density.

The F test was used to determine whether or not there was a difference between bending strengths, modulus of elasticity, spesific gravity and increase in volume values when kept in water for 2 hours obtained according to different layer organizations and if there was a difference, whether or not this difference was significant. Accordingly, there was a difference in the density, bending strength and modulus of elasticity values obtained according to the combinations of materials at $\alpha=0.5$ significance level and at a 95% confidence level and that this difference was significant ($p<0.05$).

The Duncan test was performed separately to the bending strength, modulus of elasticity, expansion in volume and air dry density values to determine among which layer organizations there was a difference and the homogeneity groups emerging at the end of the test are given separately in Tables 2 and 3.

Table 2. The homogeneity groups related to the bending strength and modulus of elasticity values obtained according to the different layer organizations.

	Homogeneity groups of bending strength (N/mm^2)				Homogeneity goups of modulus of elasticity (N/mm^2)		
Combination	1	2	3	4	Combination	1	2
ABBBBBA	52.01				BBBBBBB	5,667.90	
Lombardy poplar	55.32	55.32			Lombardy poplar	5,810.36	
BBBBBBB	57.15	57.15			BABABAB	6,316.27	
ABBABBA	62.27	62.27			ABABABA	6,316.27	
BABABAB		67.10	67.10		ABBBBBA	7,830.54	7,830.54
ABABABA			74.76	74.76	Austrian pine	8,147.81	8,147.81
AABBBAA			75.05	75.05	AABABAA	8,225.72	8,225.72
AABABAA			77.97	77.97	AAAAAAA	8,326.36	8,326.36
Austrian pine			78.82	78.82	AABBBAA	8,468.09	8,468.09
AAAAAAA				83.98	ABBABBA		9,804.63

Table 3. The homogeneity groups related to the expansion in volume and air dry density values emerging according to the different layer organizations.

	Homogeneity groups of expansion in volume (%)		Homogeneity groups of air dry density (gr/cm^3)							
Combination	1	2	Combination	1	2	3	4	5	6	7
BABABAB	10.47		Lombardy poplar	0.30						
Lombardy poplar	11.19		BBBBBBB		0.40					
AABBBAA	11.40		BABABAB			0.47				
AAAAAAA	11.72		ABBABBA			0.4784	0.4784			
ABBABBA	12.09		ABBBBBA			0.4839	0.4839	0.4839		
AABABAA	12.15		AABBBAA			0.4921	0.4921	0.4921	0.4921	
Austrian pine	12.75		ABABABA				0.4946	0.4946	0.4946	
ABABABA	13.55		Austrian pine					0.5015	0.5015	
BBBBBBB	14.44	14.44	AABABAA						0.5120	
ABBBBBA		17.77	AAAAAAA							0.5530

According to Table 2, the highest bending strength is obtained with the AAAAAAA layer organization in which all of the layers are formed from Austrian pine. However, the differences between the bending strength values obtained with the ABABABA, AABBBAA and AABABAA layer organizations and the solid Austrian pine with the bending strength values obtained with the AAAAAAA layer organization were insignificant. The differences in the bending strength values between this group and all of the other layer organizations were significant. Consequently, in case the percentage of Lombardy poplar is above 3/7, then the bending strength decreases. The lowest bending strength value emerges in the ABBBBBA layer organization in which the percentage of Lombardy poplar is 5/7.

The highest modulus of elasticity value is obtained with the ABBABBA layer organization. However, the differences between the modulus of elasticity values obtained with this layer organization and the modulus of elasticity values obtained with the solid Austrian pine and the ABBBBBA, AABABAA, AAAAAAA and the AABBBAA layer organizations were insignificant. Although the second highest modulus of elasticity value was obtained in the AABBBAA layer organization, the difference among the modulus of elasticity values obtained in all of the other layer organizations were insignificant. Accordingly, AABBBAA is the most suitable layer organization for modulus of elasticity.

The highest expansion in volume after keeping the specimens in water for 2 hours was obtained in the ABBBBBA layer organization specimens (Table 3). This was followed by the specimens with the BBBBBBB layer organization. However, when other layer organizations are not taken into consideration, the difference in the expansion in volume values emerging with these two layer organizations is insignificant. Whereas, if the ABBBBBA layer organization specimens are not taken into consideration, then the differences among the expansion in volume values of all of the other layer organizations are insignificant.

Since the air dry density of Austrian pine is high compared to Lombardy poplar, just as it is expected, the highest air dry density is obtained in the AAAAAAA layer organization (Table 3). The fact that the adhesive used in the bonding process has a higher density compared to Austrian pine causes the air dry density of this layer organization to be higher than that of solid Austrian pine. The AABABAA layer organization has the second highest air dry density. When the other layer organizations are not taken into consideration, then the differences between the air dry density values of this layer structure and the air dry density values of the solid Austrian pine and the ABABABA and the AABBBAA layer organizations were insignificant. Whereas solid Austrian pine has the third highest air dry density.

4. CONCLUSION

In connection with the tests made, the layer organization and type of wood used in the laminations were found to be significant on density, expansion in volume at the end of keeping in water for 2 hours, bending strength and modulus of elasticity of materials obtained.

Since the air dry density (0.50 gr/cm^3) of Austrian pine was high compared to that of Lombardy poplar (0.31 gr/cm^3), just as it was expected, the highest oven-dry specific gravity was obtained in the AAAAAAA layer organization. The air dry density of the laminated Austrian pine was greater than the air dry density of the solid Austrian pine. This increase in density stems from the more intensive use of adhesive in the lamination than the density of the Austrian pine. Likewise, due to the fact that it has a higher density, as the percentage of Austrian pine increases in the lamination, there is an increase in the density. Although the layer organizations vary, the differences between the density values obtained in the same Austrian pine - Lombardy poplar percentages are insignificant.

The greatest expansion in volume after keeping specimens in water for 2 hours was obtained in the specimens with the ABBBBBA layer organizations. This was followed by the specimens with the BBBBBBB layer organizations. Whereas, if the specimens with the ABBBBBA layer organization are not taken into consideration, then the differences among the expansion in volume values of all of the other layer organizations and the solid materials are insignificant. From these findings, it emerges that the highest expansion in volume occurs in the specimens, which have the maximum percentages of Lombardy poplar. Due to the fact that softwoods expand more with the sorption of water due to their cellular structures is influential on this result.

The highest bending strength is obtained with the AAAAAAA layer organization in which all of the layers are Austrian pine. This is followed by solid Austrian pine. When the other organizations are not taken into consideration, the differences among the bending strength values of the solid Austrian pine and the AAAAAAA, AABABAA, AABBBAA and ABABABA layer organizations are insignificant. This group is followed by the layer organizations in which the percentage of Lombardy poplar is greater than 3/7 and the bending strength values gradually decrease. As it is known, as the density of the wooden material increases, the strength characteristics also improve. The strength characteristics (bending strengths) of the materials obtained with an increase in the percentage use of low density Lombardy poplar decrease. According to these results, in situations where the percentage of Lombardy poplar is less than 3/7, there is no difference between the bending strengths of solid Austrian pine and laminated Austrian pine. In practice, one could be preferred over the other. Similarly, provided that the outer layers are Austrian pine, the layer organization is not influential on bending strength.

In practice, any of the layer organizations could be preferred.

The highest modulus of elasticity value was obtained in the ABBABBA layer organization. However, when this layer organization is not taken into consideration, including solid Austrian pine and solid Lombardy poplar alternatives, the differences among the modulus of elasticity values of all of the other layer organizations were insignificant. In other words, the layer organization is not influential on the modulus of elasticity. Accordingly, the most suitable layer organization for modulus of elasticity is the AABBBAA layer organization.

In conclusion, due to the fact that the spesific gravities of Austrian pine and Lombardy poplar are relatively close to each other, the differences among the values obtained for physical and mechanical characteristics are not very obvious. It is necessary to use wood types with very different densities in order to be able to obtain the expected advantages from lamination.

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