ONLINE ISSN 2069-7430
ISSN-L 1841-4737
PRO LIGNO
www.proligno.ro
Vol. 16 N° 4 2020
pp. 3-12

DETERMINATION OF THE MECHANICAL BEHAVIOR OF LAMINATED WOOD PRODUCTS UNDER DIFFERENT TEMPERATURES

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Abstract:
Ever since wood was first used as a material, its applications have continued to grow. Due to these increased applications and human population growth, the demand for wood as a raw material has also increased, resulting in more research in the field. One approach to deal with this growth in demand is the use of alternatives to solid wood, such as laminated wood products. Laminated wood has extensive industrial applications that allow it to be subject it to various physical conditions. One such parameter is temperature. Temperature changes the humidity of wood causing dimensional changes, which cause deformations at the joints of the structure. Determining the behavior of laminated wood and the adhesives used in the lamination under different temperatures is critical for a structure's service life and to the wellbeing of the users. In this study, four-point flexural strength, flexural modulus of elasticity, and compressive strength were determined for samples made from Scots pine (Pinus sylvestris) laminated using polyvinyl acetate (PVAc-D4) and polyurethane (PU-D4) glue under different temperatures. The mechanical properties of prepared samples were determined via using Zwick Z600 test machine. The results obtained in this study showed that the compressive strength of the samples has decreased with the temperature increase. The decrease in compressive strength was about 36.03% for PVAc-D4 and 34.30% for PU-D4 glue. The samples prepared using PU-D4 adhesives performed better under high temperatures in compressive strength tests.

Key words*: laminated wood; flexural strength; compressive strength.*

INTRODUCTION

Determining the behavior of laminated wood products under different temperatures should provide designers and builders with helpful information. This study was conducted to determine some mechanical properties of laminated wood products. The motivation for this study was the lack of any substantial study examining the behavior of laminated wood products under different temperature conditions.

Laminated wood materials are created by gluing two or more layers of wood and combining the fiber aspects of the layers either parallel or perpendicular to each other. If the wood that is being used is curved, the fiber aspects of the layers must be applied in parallel. When carrying out lamination, various types of trees, different number of layers, a variety of sizes, shapes and layer thicknesses can be chosen (Senay 1996). Laminated wood is one of the oldest commercial materials in the construction industry. The advances in lamination technology in recent years have played a major role in the increase of laminated wood use. Laminated wood can be produced in larger dimensions and with fewer imperfections compared with solid wood products (Peterson et al. 1981; Dilik 1997).

The mechanical properties of wood as a material deteriorate with increasing temperature and improve with decreasing temperatures. Studies show wood cannot withstand temperatures greater than 65°C for extended periods of time, as they will exhibit strength loss (Kocataskin 1966). According to previous studies, the modulus of elasticity, bending strength, tensile strength, and compression strength of wood all significantly increase with decreasing temperature (Cao et al. 2012; Jiang et al. 2014; Niemzet al. 2014; Wang et al. 2015; Zhao et al. 2015). Layer width has no effect on the flexural strength or the modulus of

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elasticity and increasing layer thickness decreases flexural strength but has no effect on the modulus of elasticity (Youngquıst et al. 1984; Yildirim et al. 2018).

A literature review shows that there are multiple studies on the physical and mechanical properties of laminated wood products produced using different wood species, adhesive types, layer thicknesses, numbers of layers, and pressures. It is stated that the bending strength of solid beams supported with a laminated layer is 10% more than those not supported with a laminated layer (Braun and Moody 1977). Studies on single - and double - layered laminated timber (fir and Southern pine) show the compressive strength parallel to the grain of double-layered samples are higher than single-layered samples (Moody 1981). It has also been found that the glue type affects the flexural strength of laminated wood, but the direction of the force has no effect (Senay 1996).

OBJECTIVE

This study aims to determine the four-point flexural strength, flexural modulus of elasticity, and the compressive strength of Scotch pine (*Pinus sylvestris* Lipsky) samples. The samples were prepared by pressing 5-mm-thick wood veneers stacked in four plies and glued together using polyvinyl acetate (PVAc-D4) and polyurethane (PU-D4) adhesives under various temperature and simultaneous loads.

MATERIALS AND METHODS

Materials

Scotch pine (*Pinus sylvestris* Lipsky) is used extensively in the wood construction sector and was used as the wooden material for these experiments. Scotch pine wood used to prepare the test samples, was obtained from timber enterprises in the Karabuk. Turkey for this study. Careful attention was paid to the fact that the wood material used in experimental studies was not subjected to physical damage, mechanical impacts or biological harm.

Adhesives

Polyvinyl acetate (PVAc-D4) and polyurethane (PU-D4) adhesives which are commonly used in the wood industry and box- type furniture manufacture, were used in this study. The single-component polyvinyl acetate (PVAc-D4) adhesive Kronen Holzleim D4 manufactured by the German Kronen Company (Fenster Technik Institut Rosenheim, Germany) was used in this study. The properties of this glue used were determined as press compression 0.1-0.8N/mm^2, pH 3.5, viscosity (20°C) 16000-15000 cps, density 1.08g/cm^3 and wood bonding time at 20°C for 35-40 minutes determined by the company. PVAc adhesive was supplied by Kronen Inc., in İzmir, Turkey (Kronen 2019). Polyurethane (PU-D4); Egger Decor, Gebze, Kocaeli, Turkey) is a single component polyurethane-based adhesive. fast curing, polyurethane based wood adhesive. Easy to apply, low viscosity and high bonding strength, resistant to water, moisture and chemicals according to D4-DIN EN204 standard. Press time at 20°C, 15-20 minutes in 65% relative humidity conditions (Romabant 2019).

Preparation of WoodLaminated Test Specimens

Veneers with dimensions of 5×70×100mm cut from Scotch pine (*Pinus sylvestris* Lipsky*)* were stacked and stored in a climate-controlled room at 20 ± 2°C and 65 ± 5% relative humidity until the moisture content of the wood reached 12% (ussualy 24-48 hours). The adhesive was applied to the broadsides of the veneers using the consumption specification of 180 to 200g/cm^2 with a brush applicator and left exposed for 5 to 6min. Then, the specimens were loaded into a hydraulic press (Hydraulic Veneer SSP-80; Cemilusta Wood Working Machinery Industry Inc., İkitelli, Istanbul in Turkey) at room temperature that applied a pressure of approximately 122N/mm^2 for 8h. After the curing period, the samples were machined to dimensions specified in the standards. Fig. 1 shows a cross-section of the specimens.

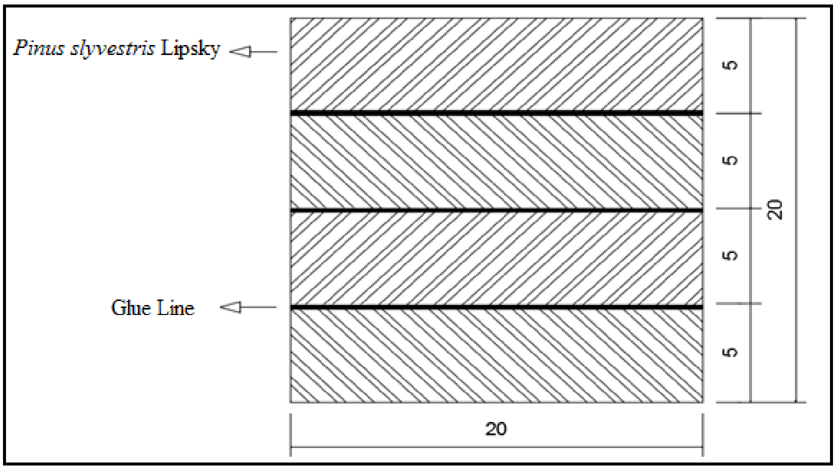

Fig. 1.
Adhesive and wood layers (dimension in mm).

METHODS
Four-point flexural test

The module of elasticity in bending was determined by complying with the TS EN 408+A1 (2015) standard. There were 36 of each of two-way test specimens prepared for every one of the adhesive and intermediary layers materials specified in the dimension of 20mm×20mm×400mm for perpendicular to the bond line or parallel to bond line. The static loads were applied using the four-point flexural test fixture (two points applied force and two points support), as shown Fig. 2. The samples were subjected to static loading in the 600-kN capacity universal testing machine Zwick Z600 test machine (Zwick Roell Z600; Zwick/Roell, Ulm, Germany at the Iron and Steel Institute at Karabuk University of Turkey) parallel and perpendicular to the bond line.

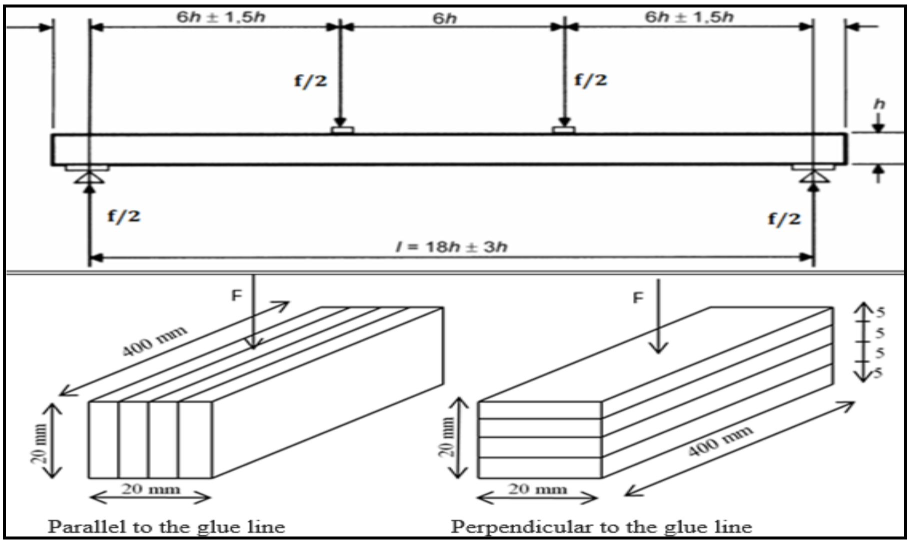

Fig. 2.
Flexural test fixture and glue plane orientation (dimension in mm).

The testing machine had a loading rate of 5mm/min. The flexural strength and flexural modulus elasticity were calculated for specimens using the 4-point flexural test fixture with a distance between supports of 315-mm span. The flexural strength is given by the following equation:

$$\sigma_{E4} = (F \times L) / (b \times h^2) \quad (1)$$

where: σ_{E4} is the four-point flexural strength (N/mm²);
F is the maximum load (N);
L is the span length (mm);
B is the specimen width (mm);
h is the specimen thickness (mm).

Flexural Modulus of Elasticity

The flexural modulus of elasticity is given by the following equation:

$$E_{mg4} = \{[\lambda^3(F_2 - F_1] / [(b_1).\ (h_1)^3(W_2 - W_1)]\} \times \{[(3a / 4\lambda) - (a / \lambda)^3\} \quad (2)$$

where: E_{mg4} is the four-point flexural modulus of elasticity (N/mm²);
λ is the measured distance for the determination of modulus of elasticity (mm);
b_1 is the specimen width (cm) (tangential);
h_1 is the specimen height (cm) (radial);
a is the minimum distance between support and load (mm);
$F_2 - F_1$ is the increment of load on the straight-line portion of the load deformation curve (N);
$W_2 - W_1$ is the increment of deformation corresponding to $F_2 - F_1$(mm).

Compressive Strength

The compressive strength parallel-to-grain was determined using the TS 2595 (1997) standard with the universal testing machine. Specimens that had dimensions of 20×20×30mm^3 were stored at 20°C and 65% relative humidity until the moisture content was 12%. Maximum load (F_{max}) at failure was measured and the compressive strength (σB//) was calculated using Eq. 3, and Fig. 3 shows specimen dimensions and the position of the applied load:

$$\sigma B// = F_{max} / (ab)\ (N/mm^2) \quad (3)$$

where: F_{max} is the maximum load at failure (N);
a is the specimen cross-section width (mm);
b is the specimen cross-section height (mm).

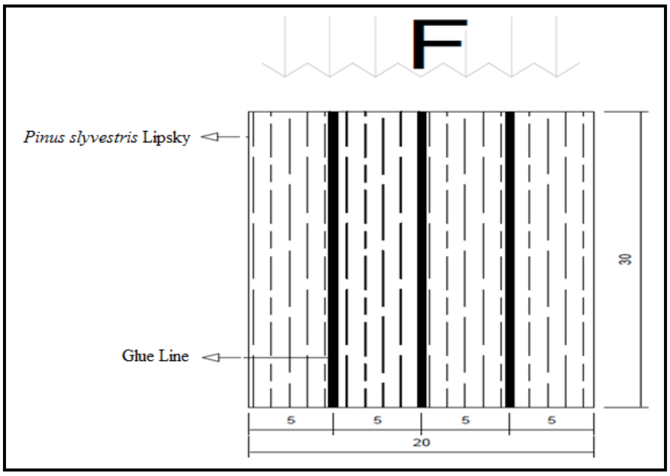

Fig. 3.
Compressive strength specimen (in size mm).

According to the statistical data from the Turkish State Meteorological Service between the years 1988 and 2017, the lowest daily total sunshine duration was in 1988 for 6.37h, and the highest daily total sunshine duration was in 1990 for 7.30h. In this study, the test specimens were kept in the testing apparatus for 8h according to the State Meteorological Service data, and a static load was applied at a displacement rate of 5mm per minute to determine the flexural and compressive parameters. To determine the flexural strength and the modulus of elasticity in flexure, the specimens were tested at 30°C, 40°C, and 50°C, along with control specimens at room temperature. To determine compressive strength, the specimens were tested at 30°C, 40°C, 50°C, 60°C, and 70°C, along with control specimens at room temperature. The testing was performed at the Karabuk University Iron and Steel Institute laboratory (Karabuk, Turkey) using a 600-kN universal testing machine fitted with an environmental chamber (Fig. 4).

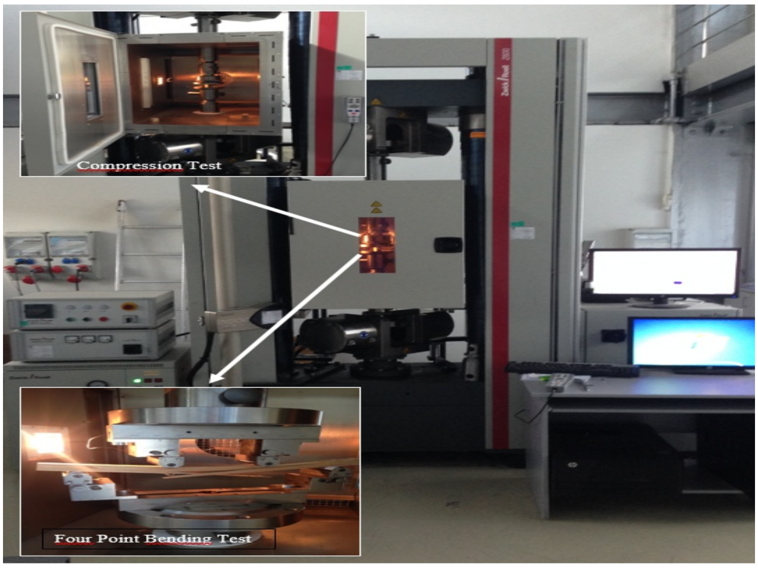

Fig. 4.
Universal testing machine.

Statistical Analysis

To determine the effects of the temperatures type, adhesive type or bond line in bonding strength and modulus of elasticity in bending, multiple analyses of variance (ANOVA) were conducted using the Statistical Software, a computer-based statistical package, Minitab, Minitab®18, Pennsylvania, State College, USA). When the differences emerged as statistically significant according to $p \leq 0.05$, the importance was determined amongst groups with the least significant difference Duncan test.

RESULTS AND DISCUSSION

Four-point Flexural Strength and Physical Properties

To determine the effects of temperature on flexural strength and flexural modulus of elasticity, control samples were tested at room temperature (25°C) and the rest of the samples were tested at three different temperatures (30°C, 40°C and 50°C). The mean values of four-point flexural strength for control and test samples, in addition to the oven-dry density of veneers and laminated samples, are given in Table 1. Multiple analysis of variance results are given in Table 2, and the Duncan test results are given in Table 3.

Table 1

Four-point Flexural Strength Mean Values (N/mm²)

Temp.(°C)	Parallel to Bond line				Perpendicular to Bond line			
	Glue Type							
	PVAc-D4		PU-D4		PVAc-D4		PU-D4	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Control	116.36	2.86	123.17	3.61	109.03	1.38	119.31	1.86
30	108.19	5.74	115.94	4.52	104.78	4.53	113.20	2.14
40	93.76	1.91	112.53	1.63	80.91	2.05	108.25	3.45
50	84.69	4.81	102.66	1.84	66.33	1.83	96.61	5.60

Veneer (0.60g/cm^3); Veneer + PVAc-D4 (0.84g/cm^3); Veneer + PU-D4 (0.82g/cm^3)

Mean: Average, SD: Standard Deviation

Table 1 shows that the flexural strength values parallel and perpendicular to the Bond line decreased with increasing temperature, especially above 40°C. The data showed the samples prepared using PU-D4 glue performed better than those prepared using PVAC-D4 glue. Results of the multiple analysis of variance on flexural strength are given in Table 2.

Table 2

Multiple Analysis of Variance Results on Flexural Test

	Sources of Variance	DF	Sum of Squares	Mean Squares	F Value	Probability of Error P < 0.05
Perpendicular to Bond line	Glue Type	1	7281.11	7281.11	714.53	0.000
	Temperature	3	13086.08	4362.02	428.070	0.000
	Glue Type × Temp.	3	1923.59	641.19	62.92	0.000
	Error	72	733.67	10.19		
	Total	80	819954.92			
	a. R Squared = 0.968 (Adjusted R Squared = 0.965)					
Parallel to Bond line	Glue Type	1	3289.54	3289.54	244.23	0.000
	Temperature	3	7617.67	2539.22	188.52	0.000
	Glue Type × Temp.	3	619.12	206.37	15.322	0.000
	Error	72	969.75	13.46		
	Total	80	93127255			
	a. R Squared = 0.922 (Adjusted R Squared = 0.915)					

DF: Degrees of freedom.

Multivariate analysis of variance results showed differences according to strength perpendicular to the Bond area and parallel to the Bond line with regards to glue type and temperature, and those interactions were statistically significant ($p<0.05$). The results of the Duncan test conducted to determine which groups had the differences are given in Table 3.

Table 3

Results of Duncan Test on the Effects of Temperature (N/mm^2)

Temp. (°C)	Parallel to Bond line		Perpendicular to Bond line	
	Mean	HG	Mean	HG
Control	119.76	A	114.17	A
30	112.06	B	108.99	B
40	103.15	C	94.58	C
50	93.67	D	81.47	D

Mean: Average, HG: Homogenity Groups.

It was determined that different temperatures had different homogeneous subsets. The results of the Duncan test parallel and perpendicular to the Bond line showed temperature was a significant factor. The effect of the glue type on the specimen's flexural strength was tested and the results of the t-test are given in Table 4.

Table 4

Flexural Strength with Regards to Glue Type t-Test Results (N/mm^2)

Bond line	Glue	Mean	(SD)	t-test	p
Parallel to Bond line	PU-D4	113.57	8.06	-6.006	0.000
	PVAc-D4	100.75	13.07		
Perpendicular to Bond line	PU-D4	109.35	1.44	-5.276	0.000
	PVAc-D4	90.27	2.83		

Mean: Average, SD: Standard Deviation

Examination of Table 4 for the t-test conducted on independent sets revealed glue type had an effect on the flexural strength parallel and perpendicular to the Bond line of samples of laminated timber ($p = 0.000 < 0.05$). The flexural strength parallel and perpendicular to the Bond line of samples prepared using PU-D4 glue was higher than the flexural strength parallel and perpendicular to the Bond line of samples prepared using PVAc-D4 glue. It can be postulated that the higher strength values were caused by the self-cohesion and adhesion properties of the PU-D4 glue and that the chemical curing helped make the PU-D4 glue more resistant to higher temperatures.

Flexural Modulus of Elasticity

A statistical assessment of the flexural modulus of elasticity of laminated timber specimens is given in Table 5 and the results of the multivariate analysis of variance are given in Table 6.

Table 5

Mean Values of Flexural Modulus of Elasticity (N/mm²)

Temp.(°C)	Parallel to Bond line				Perpendicular to Bond line			
	Glue Type							
	PVAc-D4		PU-D4		PVAc-D4		PU-D4	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Control	15321.84	351.24	15025.03	677.44	12994.10	574.43	11398.10	210.95
30	14396.16	459.38	14277.52	947.13	11811.01	305.38	11093.20	642.05
40	14055.07	379.00	13429.85	1477.22	10190.36	456.70	9476.50	635.78
50	13316.05	898.86	11512.71	2364.76	7776.20	616.53	7154.10	567.29

Mean: Average, SD: Standard Deviation

The values of flexural modulus of elasticity tested parallel to the Bond line were higher than values of flexural modulus of elasticity tested perpendicular to the Bond line. An examination of the control and 50℃ samples shows there was a 13.09% decrease in samples prepared using PVAc-D4 glue and a 23.37% decrease in samples prepared using PU-D4 glue.

Table 6

Modulus of Elasticity Analysis of Variance Results

	Sources of Variance	DF	Sum of Squares	Mean Squares	F Value	Probability of Error P < 0.05
Perpendicular to Bond line	Glue Type	1	10110456.97	10110456.97	7.83	0.007
	Temperature	3	80864587.84	26954862.61	20.89	0.000
	Glue Type × Temp.	3	8614970.47	2871656.82	2.22	0.093
	Error	72	92898254.17	1290253.53		
	Total	80	15686634302,30			
	a. R Squared = 0.968 (Adjusted R Squared = 0.470)					
Parallel to Bond line	Glue Type	1	3289.54	3289.54	244.23	0.000
	Temperature	3	263211552.62	87737184.20	319.82	0.000
	Glue Type × Temp.	3	3144342.79	1048114.26	3.82	0.013
	Error	72	19751988.76	274333.17		
	Total	80	8685956630.54			
	a. R Squared = 0.935 (Adjusted R Squared = 0.928)					

DF: Degrees of freedom.

The multivariate analysis of variance showed the effects of glue type and temperature had a different statistical significance ($p<0.05$) regarding flexural strength parallel and vertical to the Bond line. The interaction between and temperature glue type source of variation had no effect on flexural strength parallel and perpendicular to the Bond line. The results of the Duncan test performed to determine which groups had the variation are given in Table 7.

Table 7

Results of Duncan Test on the Effects of Temperature (N/mm²)

Temp. (°C)	Parallel to Bond line		Perpendicular to Bond line	
	Mean	HG	Mean	HG
Control	15173.44	A	12196.10	A
30	14336.84	B	11452.10	B
40	13742.46	B	9833.43	C
50	12414.38	C	7465.15	D

Mean: Average, HG: Homogenity Groups.

It was determined that different temperatures had different homogeneous subsets. The results of the Duncan test parallel and perpendicular to the Bond line showed temperature was a significant factor on the flexural modulus of elasticity. The effect of the glue type on the specimen's flexural modulus of elasticity was tested and the results of the t-test are given in Table 8.

Table 8

Flexural Modulus of Elasticity with Regards to Glue Type t-Test Results (N/mm²)

Bond line	**Glue**	**Mean**	**SD**	**t-test**	**p**
Parallel to Bond line	PU-D4	14272.28	8.06	2.079	0.041
	PVAc-D4	13561.28	13.07		
Perpendicular to Bond line	PU-D4	10692.92	1.44	2.131	0.036
	PVAc-D4	9780.48	2.83		

Mean: Average, SD: Standard Deviation

Examining Table 8 for the t-test results conducted on independent sets revealed that glue type had an effect on flexural modulus of elasticity parallel and perpendicular to the Bond line of laminated timber samples ($p = 0.036 < 0.05$). The flexural modulus of elasticity parallel and perpendicular to the Bond line of samples prepared using PVAc-D4 glue was higher than the flexural modulus of elasticity parallel and perpendicular to the Bond line of samples prepared using PU-D4 glue. Kasal et al. (2010) obtained similar results; in the modulus of elasticity determined that laminated materials parallel to the glue line gave higher results than laminated materials perpendicular to the glue line.

Compressive Strength

To determine the effects of temperature on compressive strength, samples were tested at six different temperatures (control, 30°C, 40°C, 50°C, 60°C, and 70°C). The mean values of compressive strength test are given in Table 9. The results of the multivariate analysis of variance are given in Table 10, and the results of the Duncan test are given in Table 11.

Table 9

Mean Values of Compressive Strength Tests (N/mm²)

Temp. (°C)	**GlueType**			
	PVAc-D4		**PU-D4**	
	Mean	**SD**	**Mean**	**SD**
Control	81.51	2.86	82.47	2.68
30	74.10	2.60	68.50	2.36
40	66.70	1.70	63.80	1.87
50	58.20	1.68	60.10	2.28
60	54.10	1.66	53.40	1.64
70	47.40	2.59	45.00	1.82

Mean: Average, SD: Standard Deviation

It can be concluded from the data in Table 9 that the compressive strength decreased with increasing temperature. The decrease in compressive strength from the starting temperature of 30°C to the maximum temperature of 70°C was 36.03% for PVAc-D4 and 34.30% for PU-D4 glue. The results of multivariate analysis of variance on compressive strength are given in Table 10.

Table 10

Compressive Strength Analysis of Variance Results

Sources of Variance	**DF**	**Sum of Squares**	**MeanSquares**	**F Value**	**Probability of Error P < 0.05**
GlueType	1	78.40	78.40	16.01	.000
Temperature	5	15981.60	3196.32	652.95	.000
GlueType × Temp. (°C)	5	169.74	33.94	6.93	.000
Error	108	528.67	4.89		
Total	120	490923.98			
R Squared = 0.968 (Adjusted R Squared = 0.965)					

DF: Degrees of freedom

Multivariate analysis of variance showed the effects of glue type, temperature, and that the interaction of the two had statistical significance ($p<0.05$). The results of the Duncan test performed to determine which groups had the variation are given in Table 11.

Table 11

Results of Duncan Test on the Effects of Temperature (N/mm²)

Temp.(°C)	Mean	HG
Control	81.99	A
30	71.30	B
40	65.25	C
50	59.15	D
60	53.75	E
70	46.20	F

Mean: Average, HG: Homogenity Groups.

It was determined that different temperatures had different homogeneous subsets. The results of the Duncan test parallel and perpendicular to the Bond line showed temperature was a significant factor. The effect of the glue type on the specimen's compressive strength was tested and the results of t-test are given in Table 12.

Table 12

Compressive Strength with Regards to Glue Type t-Test Results (N/mm²)

Glue	Mean	SD	t-test	p
PU-D4	63.67	12.00	0.745	0.458
PVAc-D4	62.05	11.78		

Mean: Average, SD: Standard Deviation

Examining Table 12 for the t-test results conducted on independent sets reveals that glue type had no effect on compressive strength of laminated timber samples ($p = 0.458 > 0.05$). The compressive strength of samples prepared using PVAc-D4 glue was higher than the compressive strength of samples prepared using PU-D4 glue.

The results of this study provided data that could be useful to designers and builders. More studies on the effects of wood type, temperature, and glue types on the mechanical properties of laminated timber should be conducted as these studies would improve the literature in this field.

CONCLUSION

The study was conducted to determine the effects of temperature on the mechanical properties of laminated timber.

1. The timber showed a decrease in flexural strength, flexural modulus of elasticity, and compressive strength as the temperature increased.
2. An examination of the compressive strength tests conducted under different temperatures showed that PU-D4 glue performed better than PVAc-D4 glue under higher temperatures.
3. The flexural tests showed the values of flexural strength and flexural modulus of elasticity were higher parallel to the bond line than perpendicular to the bond line.

ACKNOWLEDGEMENTS

This work was supported by the Research Fund of the Karabuk University (Project Number: KBUBAP-17-DS-476).

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