Physical and Mechanical Properties of Laminated Wood Made from Heat-Treated Scotch Pine Reinforced with Carbon Fiber

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Laminated veneer lumber (LVL) and reinforced laminated veneer lumber (RLVL) with carbon fiber were produced from heat-treated Scotch pine (*Pinus sylvestris* L.) wood using phenol formaldehyde (PF), polyvinyl acetate (PVAc), and polyurethane (PU) resins. Wood veneers were subjected to heat treatments at 150 °C, 170 °C, or 190 °C for 2 h before lamination. The effects of the reinforcement, heat treatment temperatures, and resins on the properties of the LVL and RLVL were analyzed. Density, equilibrium moisture content (EMC), modulus of rupture (MOR), and modulus of elasticity (MOE) were evaluated. The results showed that MOR and MOE values of solid wood and LVL specimens decreased with increasing treatment temperature. However, reinforcement with carbon fiber increased both MOR and MOE. In addition, the density values of the all RLVL specimens improved, and the EMC altered significantly for all test specimens. Compared to solid samples, the highest MOR values increased by approximately 21% in PF-RLVL samples. Similarly, the highest MOE values increased by 31% in PF-RLVL samples. In conclusion, carbon fiber, one of the most used fabric types in composites, could be utilized in the manufacture of reinforced LVL with heat-treated veneers.

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INTRODUCTION

Wood is the most preferred structural material for building and construction. It is ideal for various applications because of its advantageous properties depending on species, *i.e.*, low density, aesthetic appearance, naturally available, working properties, and especially high strength in proportion to its density (Bal and Bektaş 2013; Can *et al*. 2018). However, wood has some undesirable properties such as being dimensional instability, easily flammable, and experiencing degradation and decay from external environmental conditions (Ramage *et al*. 2017; Czajkowski *et al*. 2020). These undesirable properties restrict long-term utilization of wood as a construction material in some situations.

Forest resources and the global area of forests have declined due to various factors such as excessive use of wood material, maintenance of structures, increasing demand for wood material in the timber industry, fires, droughts, and wood pests (Aydın *et al*. 2004; Keenan *et al.* 2015; Ulusoy *et al*. 2016; İlçe 2018). This situation is a threat to humanity on a global scale (FAO 2022). These factors have increased the importance of the more effective use of wood materials, the modification of wood species of low strength, and their use in this sector, as well as the production of different materials (Pelit *et al*. 2015). Improving the durability of wood and strengthening of wood-based composite materials is important for more efficient use and protection of forest resources (De Jesus *et al*. 2012; Ulusoy *et al*. 2016).

New wood-based composite materials such as laminated veneer lumber (LVL), glued laminated timber (Glulam), oriented strand lumber (OSL), and parallel strand lumber (PSL) have been introduced to the construction industry (Güller 2001; Lam 2001; Fridley 2002; Sinha *et al*. 2011; Bal and Efe 2015). These structural composite lumbers are increasingly being used in structural applications. Wood-based composite materials are used as an alternative to solid wood in construction because of their great dimensional stability and better mechanical strength properties (De Barros Lustosa *et al*. 2015; Auriga *et al*. 2020). Laminated veneer lumber (LVL) is a high-strength engineered wood product and one of the most commonly used engineered wood products for construction. The demand for engineered wood products such as LVL materials is increasing in the construction industry (Moradpour *et al*. 2018).

Heat treatment is an alternative and an effective wood modification method for improving the dimensional stability and durability of wood with no use of chemical additives (Nazerian and Dahmardeh Ghalehno 2011; Poncsak *et al*. 2011; Hill *et al*. 2021). Heat treatment changes the chemical composition, structure, and properties of wood (Esteves *et al*. 2013; Xing *et al*. 2020; Marcon *et al*. 2023). Sernek *et al*. (2008) studied the effect of heat treatment on bonding properties of Norway spruce (*Picea abies* Karst), Douglas fir (*Pseudotsuga menziesii* Franco), poplar (*Populus* species), birch (*Betula pendula*), and alder (*Alnus glutinosa* Gaertn). Heat treatment affects the shear strength and the delamination of the laminated wood, depending on the adhesive system used for bonding. Heat-treated woods are used in indoors (kitchen furniture, paneling, and parquets) and outdoor applications (garden furniture, windows, doors, and wall or fence boarding) due to their excellent properties, environmental friendliness, and appearance (Rapp 2001). One disadvantage of heat treatment is that it significantly reduces the mechanical strength and flexibility of the wood material (Chen *et al*. 2020).

The decrease in the mechanical strength of heat-treated wood material limits its use in industrial applications where strength properties are important (Bayani *et al*. 2019; Nhacila *et al*. 2020; Ali *et al*. 2021). The amount of changes after heat treatment depends on the initial moisture of the wood, the heat treatment temperature and the duration, the species of wood, the density of the wood, the extractive content of the wood, the surrounding atmosphere, and the heat treatment method, *etc*. (Bal 2015; Reinprecht 2016; Ali *et al*. 2021). Wood has natural defects such as knots, cracks, *etc*., along with its favourable properties (Çolak and Değirmentepe 2020). These defects adversely affect the mechanical properties and the use of wood under bending loads (Corradi *et al*. 2021). Physical and mechanical properties of wood materials can be improved by some modification process. Various reinforcing systems have been developed to improve the mechanical properties of wood and wood-based materials and to increase the load capacity of timber (Borri *et al*. 2005; Basterra *et al*. 2012; Jasieńko and Nowak 2014; Schober *et al*. 2015; Valenca *et al*. 2015; Song *et al*. 2017; Brol and Wdowiak-Postulak 2019; Yerlikaya 2019; Balmori *et al*. 2020; Zhou *et al*. 2020). These deficiencies can be improved by using engineered fibers reinforcement.

Wood-based composites reinforced by carbon fibers are being used extensively for many structural applications. In recent years, carbon fiber fabrics have been widely used for reinforcing LVL materials (Fiorelli and Dias 2003; Perçin and Altunok 2017; Rescalvo *et al*. 2020; Perçin and Uzun 2022). Reinforcing fiber technology is an effective and applicable method for improving the strength properties of LVL produced from low-quality wood materials. Therefore, reinforced LVL can be an alternative to high quality solid wood (Wang *et al*. 2015). Wei *et al*. (2013) studied the modulus of rupture (MOR) and the modulus of elasticity in bending (MOE) of poplar LVL reinforced by carbon-fiber-reinforced polymer (CFRP) in two different configurations. They reported that poplar LVL reinforced with CFRP had higher MOR and MOE values than the control LVL. Bal (2014a) conducted experiments to determine the effect of reinforcing process with woven glass fibers on some physical and mechanical properties LVL. He found that reinforcing process increased density, impact bending, and shear strength of LVL, in addition tangential and volumetric swelling, moisture content, and specific impact bending strength decreased. De la Rosa García *et al*. (2013) studied the bending properties of pine beams reinforced with basalt and carbon fibers. They reported that reinforced beams with reinforcing fiber showed significant increases in mechanical properties to which BFRP fibers and bi-directional carbon fabrics were applied. Rescalvo *et al*. (2018) carried out experimental and analytical work on bending load capacity of old timber beams reinforced with carbon fiber strips. They stated that improvements of up to 88% in the mechanical properties of the reinforced beams could be achieved, depending on the amount and location of the defects. Shekarchi *et al*. (2020) carried out an experimental study to evaluate the flexural behavior of timber beams strengthened by pultruded glass fiber reinforced polymer profiles. The test results showed that the bending strength, flexural rigidity, and ductility of reinforced beams were improved by up to 61, 59, and 79% according to unmodified specimens, respectively.

Many studies have investigated the effect of reinforcing materials on the physical and mechanical properties of unheated-wood, wood-based material, and LVL. Perçin and Altunok (2017) studied heat-treated (160, 190, and 220 °C) beech veneers that were strengthened with carbon fiber fabric using DVTKA glue. They analyzed some physical and mechanical properties. However, a detailed and extensive study of LVL produced from heat-treated wood has not been reported. In addition, determining the effect of reinforcing materials on improving the mechanical properties of heat-treated LVL may be important in terms of using heat-treated materials in load-bearing systems. The present study determined the effect of the addition of carbon fibers between wood layers bonded with phenol formaldehyde (PF), polyvinyl acetate (PVAc), and polyurethane (PU) adhesives on selected physical and mechanical properties of the manufactured specimens using heat-treated scotch pine (*Pinus sylvestris* L.) veneer.

EXPERIMENTAL

Wood Material

Scotch pine (*Pinus sylvestris* L.) timber beams measuring 30 × 120 × 2400 mm (Radial × Tangential × Longitudinal) with 13.11% moisture content and 0.509 g/cm^3 air-dried density were purchased from a commercial company in Turkey. Wood samples of dimension 20 mm × 110 mm × 930 mm (R × T × L) were cut from these beams for heat treatment process. Four groups of materials, consisting of one group without treatment (untreated wood) and three groups with heat treatment, were prepared. Samples were conditioned at a temperature of 20 ± 2 °C and 65 ± 5% relative humidity before heat treatment until the weight of the wood was stabilized.

Carbon Fiber

Carbon fiber was used in this study as reinforcement for heat-treated veneers. Although carbon fibers have low density, they have superior tensile strength, modulus of elasticity, as well as fatigue properties. For these reasons, they are used in various applications that require strength to fatigue and carrying capacity of beams (Auriga *et al*. 2020). The plain-weave carbon fibers were purchased from Dost Kimya Industrial Raw Materials Industry and Trade Ltd. Co in Istanbul, Turkey. According to data provided by the manufacturer, the tensile strength is 3800 MPa, the tensile modulus is 240 GPa, the areal weight (gram/sq/m) is 200 (± 5%), the tensile strain is 1.6%, and the actual carbon content in the fiber is 95%.

Adhesives

For testing the physical and mechanical properties, commercially available adhesives from different producers were used. For the lamination process, polyvinyl acetate (PVAc), phenol formaldehyde (PF), and polyurethane adhesive (marine & marine AA) (PUR) were used as binder. The adhesives were obtained from Polisan and Gentaş producer firms in Turkey. Although these adhesives have different properties, they were selected as test materials because of commonly usage of woodworking and construction industries. The adhesives have been commonly used for the manufacture of wood-based composites and in woodworking industry, and also their properties are given Table 1.

Table 1. Technical Properties of Adhesives Used

	Density (g/cm^3)	pH (25 °C)	Viscosity (cPs) (25 °C)	Amount Applied (g/m^2)
PUR	1.110	7.0	3000-5500	180-200
PF	1.120	8.4-8.8	350-450	180-200
PVAc	1.110	6-7.5	10000-14000	180-200

Heat Treatment

Before LVL production, the specimens were heat-treated at three temperature levels of 150, 170, and 190 °C for 2 h. The heat treatment was conducted in a heating chamber which into heated steam could be injected.

During the heat treatment, 1 bar of water vapor (100 ± 3 °C) was sprayed into the heating chamber at intervals of 200 seconds for 5 seconds. The heat treatments were carried out in three stages. First, temperature was raised rapidly using heat and steam to a level of 100 °C for 5 h. Thereafter, the temperature was increased steadily to 130 °C for 10 h. Secondly during actual heat treatment temperature was increased to a level of 150, 170, and 190 °C for 5 h. When the target temperature was reached, the oven temperature was kept constant for 2 h. In the last stage, the oven temperature was decreased to approximately 30 °C for 13 h. As an example, the heat treatment at 190 °C is shown in Fig. 1. Heat treatment applications at 150 and 170 °C were also carried out according to this plan.

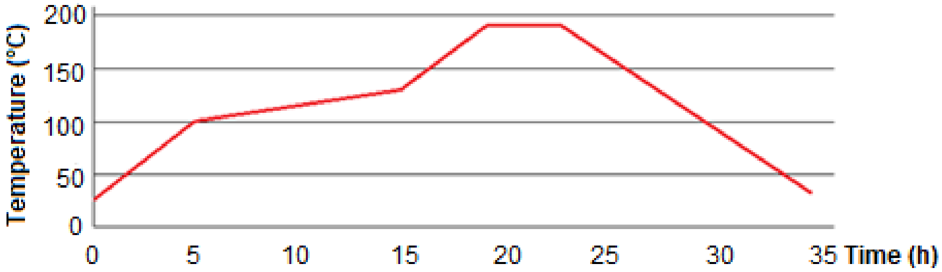

Fig. 1. Schematic presentation of the heat treatment plan at 190 °C

Production of LVL and RLVL Panels

The veneers used to manufacture LVL were 4-mm thick and made from sawn veneer Scotch pine (*Pinus sylvestris* L.) wood. The heat-treated and untreated specimens were cut into small veneer sheets dimensions of 4 × 100 × 800 mm (R × T × L) and conditioned sufficiently in a climate chamber at a temperature of 20 ± 2 °C and of 65 ± 5% relative humidity for further lamination process. These veneer sheets were used to produce LVL boards using PF, PVAc, and PU adhesives. One group was used to produce LVL, and the other group was used to produce RLVL. The RLVL panels consisted of five veneers and four layers of carbon fiber in between them, while LVL specimens consisted of only five veneers. The LVL manufacturing process was carried out at a temperature of 20 ± 2 ºC and 65 ± 5% relative humidity. In the lamination production process, 180 g/m^2 of adhesive was applied between the wood veneers and 290 g/m^2 of adhesive was applied between the veneer and carbon fiber fabric, taking into account the manufacturer's recommendations and the surface roughness of carbon fiber fabric.

Different time and temperature parameters were applied for the pressing process due to adhesives properties and producer’s recommendations. In the manufacturing process, 1.1 N/mm^2 pressure was applied in the production of all test specimens. Press time and temperature were 30 min and 130 °C for PF, 200 min and 25 °C for PU, and 240 min and 22 °C for PVAc, respectively, by taking the general curing temperatures recommended by their manufacturers into consideration. After the pressing process, the panels were stored for a week for complete curing. The test specimens were prepared from these LVL and RLVL panels. The manufactured LVL and RLVL specimens were conditioned at 20 ±2 °C and of 65 ± 5% relative humidity for three weeks before tests. Ten test specimens were prepared for each group with dimensions of the MOR and MOE test samples for LVL were 20 × 20 × 360 mm (height × width × length), for RLVL 21 × 20 × 360 mm (height × width × length) and the span was 300 mm. Veneers used in the production of test specimens are given in Fig. 2.

Fig. 2. Veneers used in the production of test specimens. Left: untreated veneers, Right: heat-treated veneers

Structures of test specimens are given in Fig. 3.

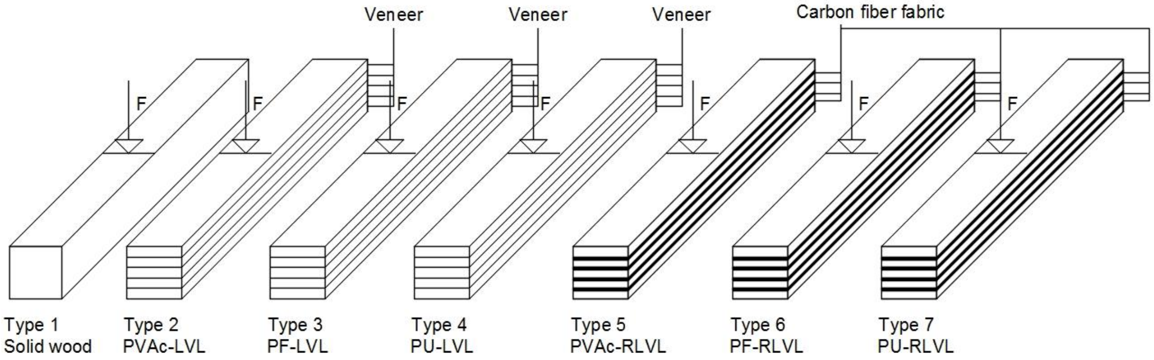

Fig. 3. Structure of test specimens

Mechanical Properties

The static bending strength (MOR) and modulus of elasticity in bending (MOE) were tested according to the TS 2474 (1976) and TS 2478 (1976) standards in the flatwise direction. All mechanical tests were carried out in a universal test machine (Instron 5969, capacity with 50 kN) according to the related standards. The test velocity of the three-point bending test was selected to be 2.5 mm/min, and specimens were loaded until broken. Scheme of the static bending test is given Fig. 4.

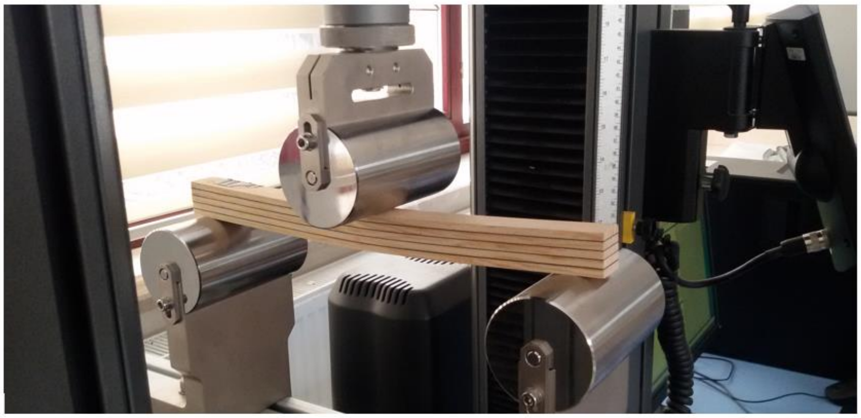

Fig. 4. Scheme of the static bending test

Physical Properties

The density values of LVL and RLVL specimens were measured according to TS EN 323 (1999) equilibrium moisture contents TS EN 322 (1999) standards. The test specimens used to determine the air-dry density and EMC values were kept at a temperature of 20 ± 2 °C and 65 ± 5% relative humidity until they reached a constant weight before the properties were determined.

Statistical Analyses

The computer-based statistical software package MSTAT-C was used. For significant differences between factors, analysis of variance (ANOVA) at a 0.05 significance level was used. A comparison of the means was performed by Duncan test with 0.05 significance level.

RESULTS AND DISCUSSION

The density parameters obtained from the experiments are given in Fig. 5. The effect of reinforcing process and heat treatment factors on density were statistically significant ($p \leq 0.05$). The highest density value was found in the PF-RLVL test specimen without heat treatment (0.552 g/cm^3), and the lowest in the solid wood that was heat-treated at 190 °C (0.484 g/cm^3). An increase in density was observed for all specimens made with the addition of carbon fibers, and density values of the reinforced specimens were higher than the solid and unreinforced specimens. This increase was expected due to the higher density of the carbon fiber. The use of high-density carbon fiber between wood veneers may have resulted in an increase in density. In addition, more adhesive was applied to carbon fiber than wood veneers, which may have contributed to the increase in density. Wei *et al*. (2013) reported that the use of carbon fiber between poplar veneers increased the density values of LVL specimens. Another related study on reinforced scotch pine LVL also reported that reinforcing process with carbon fiber also contributes to the density of specimens (Özyurt and Ayrılmış 2018).

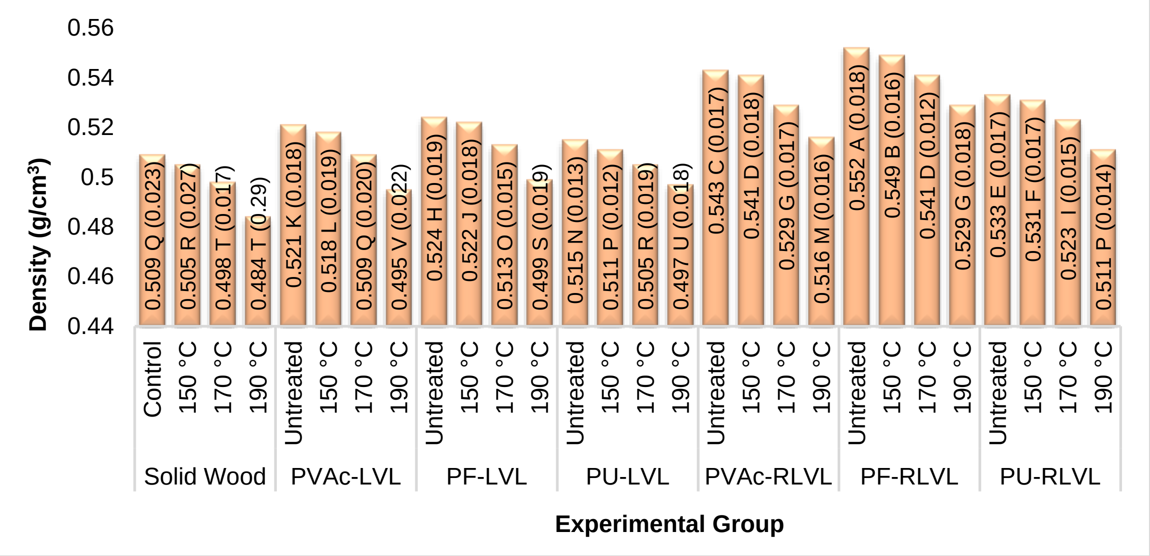

Fig. 5. Density values of tested specimens; Note: In the Fig. 5, means with different letters within each column differ significantly ($P \leq 0.05$) according to Duncan's test. Standard deviations are given in parentheses.

The densities of specimens decreased after heat treatment. The density values of specimens that had been heat-treated at higher temperature were lower than those treated at lower temperature. As the heat treatment temperature increased, the density values decreased and the highest decrease in density was seen at 190 °C. The decrease in density at maximum temperature ranged from 3% to 5%. The density decrease can be explained by a loss of mass in the wood material due to heat treatment and the decrease in the equilibrium moisture content. In the previous study, it was stated that the main reasons for the decrease in density after heat treatment were: degradation of wood components (mainly hemicelluloses) into volatile products which evaporate during treatment; evaporation of extractives; and a lower equilibrium moisture content of the specimens because of heat-treated wood is less hydrophobic (Boonstra *et al*. 2007a). Durmaz *et al*. (2019) found similar results for Scotch pine (*Pinus sylvestris* L.) specimens in their study. In another study, Korkut and Bektas (2008) studied that effect of heat treatment on density values of Uludag Fir (*Abies bornmuelleriana* Mattf.) and Scotch pine wood. They reported that heat treatment decreased density of both wood specimens.

Figure 5 shows that the specimens bonded with PF were denser than those bonded with PVAc and PU. This result can be explained by the press conditions during the bonding of the specimens with PF.

The average of EMC values obtained in different treatments are shown in Fig. 6. The heat-treatment temperature and adhesive type factors were statistically significant relative to EMC ($p \leq 0.05$). According to Fig. 6, EMC appeared to decrease depending on the increase of the heat treatment temperature. Heat treatment at 190 °C resulted in the lowest value for the EMC. On the other hand, the highest EMC was determined in the specimens that were not untreated, followed by the specimens that were heat-treated at 150 °C. The reduced EMC of heat-treated wood can be explained by several factors, including the degradation of the amorphous regions of cellulose, triggering cross-linking reactions that potentially hinder moisture intake (Jermer *et al*. 2003; Mitani and Barboutis 2014; Adeyemi *et al*. 2017). As is well known, hygroscopicity is highly related to the accessible hydroxyl groups of wood and the EMC of heat-treated wood becomes considerably reduced (Hill *et al*. 2021). The reduction in hygroscopicity after heat treatment is probably due to the reduction of the hydrophilic groups in present study. Sivrikaya *et al*. (2020) stated that the EMC values of Scotch pine specimens decreased significantly after heat treatment. Additionally, similar results were reported by Kamperidou *et al*. (2014). They applied Scots pine wood to heat treatment under atmospheric pressure at 200 °C for varying durations (4, 6, and 8 h). They reported that EMC decreased after the modification due to the mass loss (hemicelluloses degradation) and the hydroxyl groups losses.

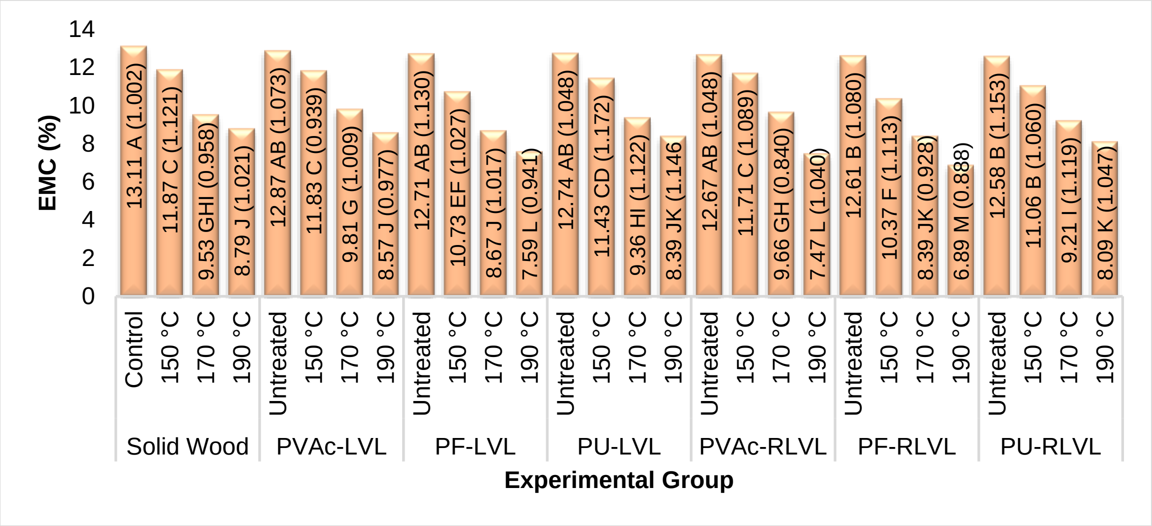

Fig. 6. EMC values of tested specimens. Different letters in each column (homogeneous groups) indicate statistically significant difference between the groups ($p \leq 0.05$) by Duncan's multiple comparison test. Standard deviations are given in parentheses

The EMC values of LVL and RLVL were slightly different from each other in relation to the adhesive type, and also they were lower than solid wood. These differences may be due to the different structural properties of the adhesive type and also adhesive lines can be caused by reduced moisture transport across veneers. In addition, it is seen that the EMC values of the laminated samples decreased when compared to the solid samples. This could be explained by the fact that the adhesives have a hydrophobic property. Bal and Bektaş (2012) studied that EMC of LVL composites made of poplar, beech, and eucalyptus woods using urea formaldehyde (UF), melamine urea formaldehyde (MUF), and phenol formaldehyde (PF) adhesives. They reported that EMC values were between 8.45% and 9.90%, and they were lower than the values for solid wood. They also declared that this situation is due to the hysteresis in hot press applications and the fact that the adhesive layers limit moisture transport across the wood veneers.

Table 2 shows the mean values, standard deviations, and coefficients of variation of MOR and MOE of solid wood, LVL, and RLVL. ANOVA results show that the effects of heat treatment and reinforcing factors on MOR and MOE of Scotch pine woods were statistically significant ($p \leq 0.05$). Heat treatment had a significant effect on MOR and MOE values of all the test specimens. In general, heat treatment decreased MOR and MOE. Although heat treatment reduced the mechanical strength attributes, they were increased depending on reinforcing and lamination process in comparison with solid wood. Increases or decreases in MOR and MOE were not stable; indeed, they fluctuated. Heat treatment influenced the MOR and MOE differently. Both MOR and MOE decreased more at 190 °C. These results demonstrate that high-temperature evidently affected the MOR and MOE of the all test specimens.

Regarding effects of the reinforcing process and heat treatment variables, the highest MOR and MOE were found to be in the specimens that were reinforced with carbon fibers and laminated specimen with PF adhesive using heat-treated veneers at 150 °C (108.2 and 12900 N/mm^2, respectively), and the lowest were found in the specimens unreinforced and laminated specimen with PVAc adhesive using heat-treated veneers at 190 °C (68.28 and 7568 N/mm^2 respectively). However, MOR and MOE values of all reinforced LVL specimens were higher than unreinforced LVL and solid wood subjected to heat treatment under the same conditions. The most successful results in terms of MOR and MOE for all specimens were found in laminated specimens with PF adhesive. The density values of the specimens laminated with PF adhesive were slightly higher than others. Therefore, using carbon fiber fabric and PF could improve the MOR and MOE of LVL specimens in this study.

The MOR and MOE values of all reinforced specimens laminated with using three different adhesive increased compared to unreinforced specimens and solid specimens that were heat-treated at the same condition. In specimens with high density, MOR and MOE values of reinforced specimens generally tend to increase for three adhesives. After heat treatment, both mechanical strengths of the specimens exposed to high temperatures decreased. The increase in MOR and MOE of the specimens by the reinforcement process with carbon fiber is consistent with previous studies (Basterra *et al*. 2012; Šedivka *et al*. 2015; Wang *et al*. 2015; Fotouhi *et al*. 2020; Auriga *et al*. 2020).

Average comparison analysis of experimental groups and heat treatment temperatures on MOR are shown in Fig 7. PF-RLVL showed highest MOR value, followed by PVAc-RLVL, PF-LVL, PU-RLVL, PU-LVL, solid wood, and PVAc-LVL, respectively. The values of the MOR of the reinforced specimens were significantly higher by 21% for PF-RLVL, 12% for PVAc-RLVL, and 9% for PU-RLVL than those of the solid wood. In addition, the MOR values of the unreinforced specimens were higher by 12% for PF-LVL and 1% for PU-LVL, except for PVAc-LVL, than those of the solid wood. In the present study, MOR values of solid wood were slightly higher than unreinforced and laminated specimens with PVAc adhesive only (PVAc-LVL).

Table 2. Mean Values, Standard Deviations and Coefficients of Variation of MOR and MOE of Solid Wood, LVL and RLVL

Experimental Group	Heat Treatment (°C)	MOR			MOE		
		Mean (N/mm^2)	SD	COV	Mean (N/mm^2)	SD	COV
Solid Wood	Control	93.24 HIJ	2.51	2.69	10280 HIJ	273.7	2.66
	150	91.75 JK	1.91	2.08	9987 KL	112.8	1.13
	170	85.49 L	2.81	3.29	9414 M	132.2	1.40
	190	72.48 O	4.40	6.07	7998 P	189.8	2.37
PVAc-LVL	Untreated	94.77 GH	2.64	2.78	10460 HI	302.1	2.89
	150	94.53 GH	2.14	2.26	10740 G	212.3	1.98
	170	80.34 M	2.40	2.98	9047 N	189.2	2.09
	190	68.28 P	2.61	3.2	7568 Q	341.8	4.52
PF-LVL	Untreated	97.89 DEF	3.04	3.11	10980 F	356.7	3.25
	150	99.78 CD	2.34	2.35	11110 EF	203.0	1.83
	170	98.12 DE	2.86	2.91	10260 IJ	186.2	1.82
	190	85.71 L	2.40	2.79	9426 M	193.0	2.05
PU-LVL	Untreated	94.85 GH	1.43	1.51	10450 HI	254.9	2.44
	150	95.72 FG	1.99	2.08	10050 KL	222.6	2.22
	170	81.74 M	1.97	2.41	9149 N	134.1	1.47
	190	76.62 N	2.03	2.65	8459 O	178.6	2.11
PVAc-RLVL	Untreated	99.48 CD	2.34	2.36	11180 E	223.8	2.00
	150	101.2 C	2.06	2.04	11860 D	140.1	1.18
	170	96.47 EFG	1.66	1.72	10160 JK	140.8	1.39
	190	89.78 K	2.08	2.32	9487 M	118.6	1.25
PF-RLVL	Untreated	103.6 B	2.34	2.26	12290 C	308.3	2.51
	150	108.2 A	1.84	1.70	12900 A	159.9	1.24
	170	105.5 B	1.88	1.79	12580 B	168.9	1.34
	190	97.78 DEF	1.34	1.37	11680 D	194.0	1.66
PU-RLVL	Untreated	97.48 DEF	1.40	1.44	10970 E	209.8	1.91
	150	99.17 CD	2.04	2.06	11870 D	227.2	1.91
	170	92.47 IJ	2.03	2.20	10470 H	193.3	1.85
	190	85.78 L	1.59	1.85	9848 L	146.6	1.49

Note: Different letters in each column (homogeneous groups) indicate statistically significant difference between the groups ($p<0.05$) by Duncan's multiple comparison test,
PVAc-LVL: Laminated veneer lumber with PVAc,
PF-LVL: Laminated veneer lumber with PF,
PU-LVL: Laminated veneer lumber with PU,
PVAc-RLVL: Reinforced laminated veneer lumber with PVAc; PF-RLVL: Reinforced laminated veneer lumber with PF; PU-RLVL: Reinforced laminated veneer lumber with PU; SD: Standard deviation; COV: Coefficient of variation.

These results indicated that the MOR values of the reinforced specimens improved after reinforcement process. MOR strengths of three types of reinforced LVL specimens were higher than that of the unreinforced LVL specimens. Compared to unreinforced LVL specimens, MOR values of PF-RLVL, PVAc-RLVL, and PU-RLVL specimens increased by 8%, 14%, and 7%, respectively. Besides, a better reinforcement effect was obtained with PF adhesive in this study. Higher increase was obtained in PF adhesive compared to PVAc and PU adhesives. According to Fig. 7, the highest MOR was obtained from PF adhesive, while the lowest was with PVAc adhesive. Also, the highest MOR according to the heat treatment temperature was determined at 150 °C. According to Fig. 7, MOR values decreased due to the increase in heat treatment temperature. A reduction in MOR has been reported and explained by the changes in content and structure of hemicelluloses induced by the heat treatment, causing loss of bending strength of wood material (Boonstra *et al*. 2007b; Korkut *et al*. 2008).

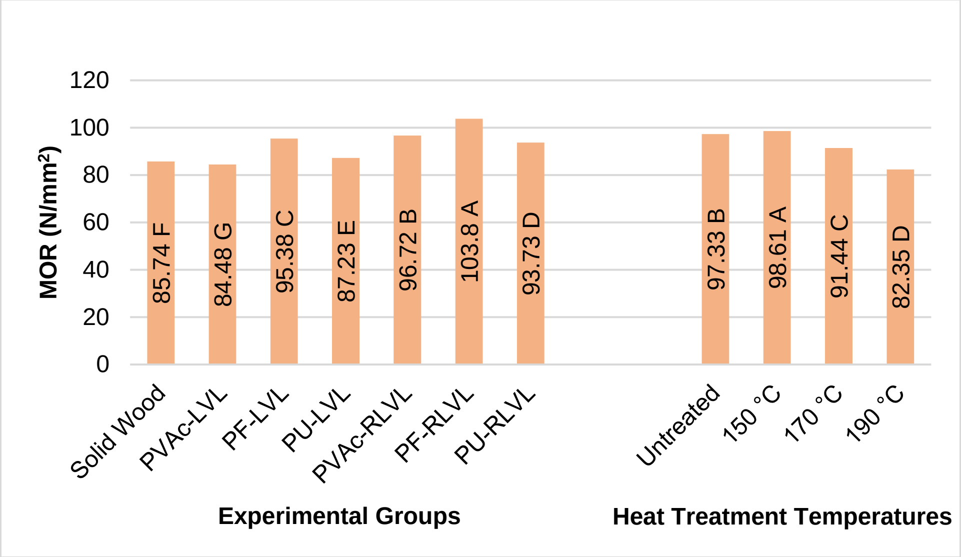

Fig. 7. MOR values for experimental groups and heat treatment temperatures. Different letters in each column (homogeneous groups) indicate statistically significant difference between the groups ($p<0.05$) by Duncan's multiple comparison test.

The effect of experimental groups and heat treatment temperatures on MOE are shown in Fig. 8. The MOE values of wood specimens increased, depending on the reinforcing process. Similarly, the highest MOE was determined in PF-RLVL, followed by PU-RLVL, PVAc-RLVL, PF-LVL, PU-LVL, PVAc-LVL, and solid wood, respectively. Figure 8 shows that the MOE values of PF-RLVL, PU-RLVL, PVAc-RLVL, PF-LVL, PU-LVL, PVAc-LVL were higher than those of the solid wood, by 31%, 14%, 13%, 10%, 1% and about 1%, respectively.

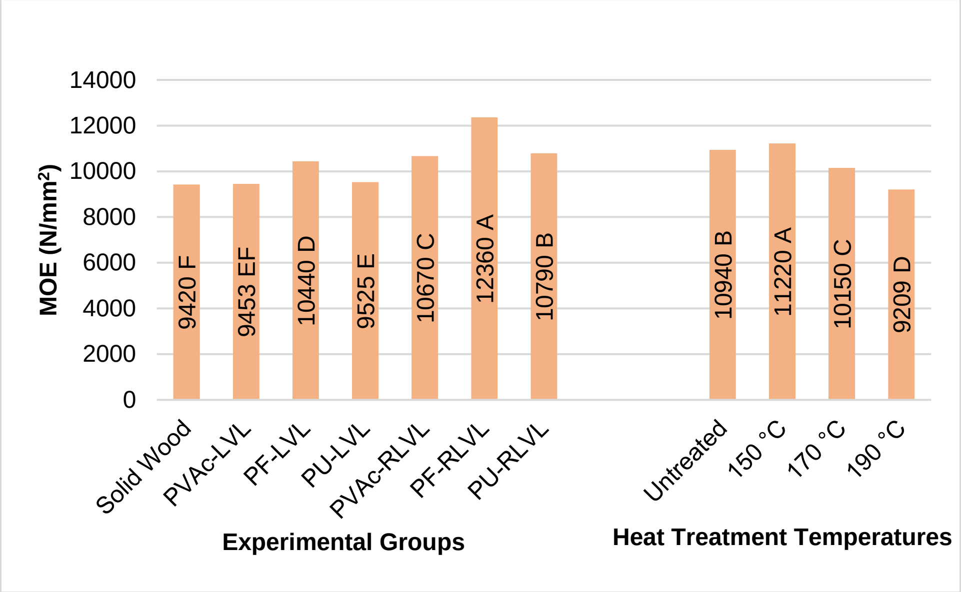

Fig. 8. MOE values for experimental groups and heat treatment temperatures. Different letters in each column (homogeneous groups) indicate statistically significant difference between the groups ($p<0.05$) by Duncan's multiple comparison test

In addition, MOE values of PF-RLVL, PU-RLVL, PVAc-RLVL are significantly higher than PF-LVL, PU-LVL, PVAc-LVL, by 18%, 13% and 12%, respectively. The MOE value of the test specimens changed significantly, depending on the heat treatment conditions. With respect to heat treatment, the highest MOE was found to be in the specimens heat-treated at 150 °C, while the lowest MOE was obtained in the specimens where heat treatment was applied at 190 °C. The MOE values decreased significantly, depending on the increase in the heat treatment temperature.

With regard to Figs. 7 and 8, MOR and MOE increased at the initial stage of the heat treatment and decreased later. Previous studies reported that there is a slight increase in MOR and MOE values after heat treatment at low temperature and short-term heat treatment application (Bekhta and Niemz 2003; Poncsak *et al*. 2006; Shi *et al*. 2007). Esteves and Pereira (2009) reported that the modulus of elasticity increases for moderate heat treatment and decreases for more severe heat treatment due to increasing crystallinity of the cellulose and the reduction of equilibrium moisture content. MOR and MOE properties of heat-treated wood were extensively studied previously and different results due to the treatment process, temperature, duration, and wood species were reported (Kocaefe *et al*. 2008; Gunduz *et al*. 2009; De Oliveira Araújo *et al*. 2016; Ninane *et al*. 2021; Yang *et al*. 2022).

The MOR and MOE values from Table 2 show that the all reinforced specimens with carbon fiber had higher MOR and MOE than those of all unreinforced specimens and solid wood. In the literature, it has been reported that the density increases with the reinforcement of LVL with reinforcing fabrics and the application of greater amount adhesive between the lamellas (Bal 2014b; Perçin 2016; Bal 2017). This would result in an increase in mechanical properties of reinforced specimens. There is a generally positive relationship between the mechanical properties of wood material and its anatomical structure and density (Miyoshi *et al*. 2018; Pelit and Emiroglu 2021). The increases in PF can be explained by the characteristics of this adhesive and the production conditions of the test specimens. The temperature applied during the production of the test specimens with PF may have caused to thermo-mechanical densification and consequently this situation may have been caused an increase in MOR and MOE. In previous studies, it was reported that the mechanical properties of bonded wood materials produced using different adhesives change depended on the type of adhesive, press pressure, press temperature, and press time (Uysal *et al*. 2010; Altinok *et al*. 2011; Kurt *et al*. 2011; Onat and Özdemir 2020).

CONCLUSIONS

1. The effects of reinforcing process and heat treatment on some physical and mechanical properties of Scotch pine (*Pinus sylvestris* L.) wood specimens were investigated. The reinforcing process, adhesive type, and heat treatment significantly affected density values of specimens. The densities of all the specimens increased depending on reinforcing process with carbon fiber. The highest density was found in the PF-RLVL test specimens without heat treatment, and the lowest in the solid wood that was heat-treated at 190 °C.
2. Equilibrium moisture content (EMC) values decreased depending on the heat treatment temperature. Heat treatment at 190 °C was resulted the lowest values for the EMC. On

the other hand, the highest EMC was determined in the solid wood specimens that were untreated (control). In addition, EMC values alters depending on heat treatment, reinforcing process and adhesive type.

3. Test results indicate that the strength properties were dramatically affected by heat treatment and reinforcing process. MOR and MOE values of all RLVL were higher than solid wood and LVL specimens. In addition, in general, the MOR and MOE of the LVL were higher than that of solid wood. There was a general increase in the MOR and MOE for all RLVL, while the increase in mechanical properties was primarily due to the inclusion of the reinforcement process. Better mechanical properties were found in specimens that were laminated with PF and reinforced specimens using veneers subjected to heat-treated at 150 °C. Compared to solid samples, the highest MOR values increased by approximately 21% in PF-RLVL samples, in the same way the highest MOE values increased by 31% in PF-RLVL samples.
4. According to the experimental results in MOR and MOE the carbon fiber fabric supporting material increased strength properties of heat-treated laminated wood material, it is suggested that carbon fiber fabric could be used to manufacture stronger heat-treated laminated veneer lumber.

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