Properties of Heat-Treated Beech Laminated Veneer Lumber Reinforced with Carbon Fiber Fabric

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Carbon fiber fabric reinforced laminated veneer lumber (RLVL) pieces were prepared by using heat-treated beech (*Fagus orientalis* Lipsky) veneers with polyurethane (PU) adhesive as the binder. Carbon fiber fabric was tested in three different locations with solid material and non-reinforced samples (on the bottom adhesive line, upper adhesive line, and upper and bottom adhesive lines-symmetrical). Prior to the manufacture of LVL and RLVL, heat treatment was conducted in a laboratory oven at three temperatures. These temperatures were 150, 170, and 190 °C. Tests were performed on LVL and RLVL to determine their air-dried density, modulus of rupture (MOR), and modulus of elasticity in bending (MOE). Experimental test results showed that reinforcement with carbon fiber increased the air-dried density, MOR, and MOE. In addition, carbon fiber fabric placed symmetrically close to bottom and upper surfaces gave the highest MOR and MOE values. However, locating the carbon fiber fabric closer to the bottom surface tended to give higher mechanical properties for the reinforced LVL.

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INTRODUCTION

Wood is a renewable and sustainable material with long term use. Therefore, it is one of the oldest building materials in human history. It has been used by societies around the world for thousands of years. Although wood is a building material that is commonly used due to some of its favorable properties, there are improvements that can be made to further enhance it for the market (Ramage *et al.* 2017; Blanchet and Pepin 2021; Wang *et al.* 2022; De Santis *et al.* 2023). The world's forest resources have continued to decline, emerging as a threat to the future of the world and humanity on a global scale (FAO 2022). Due to this, it is vital to ensure sustainable growth and adequate management of forest resources (Ryabukhin *et al.* 2022). It is also important to use forest resources efficiently (Pelit *et al.* 2015).

Forest resources can be used efficiently by removing the defects of the wood material and producing new wood-based composite materials with the lamination technique (Karayılmazlar *et al.* 2007; Kılıç 2017). Wood-based composites are commonly used for structural applications as alternative materials to solid wood due to their greater dimensional stability and durability. The most used wood-based composites are layered materials, such as laminated veneer lumber (LVL). They are layered composites with better mechanical strength properties and stiffness than the raw material itself (Auriga *et al.* 2020).

Physical and mechanical properties of wood materials can be improved through various strengthening methods applied during the production of laminated wood material. They can also be improved with reinforcing systems such as metal materials and synthetic fibers used for strengthening purposes (Karaman *et al.* 2021). The most used reinforcement materials among fiber-reinforced polymer composites (FRPC) are glass fibers, carbon fibers, aramid fibers, natural fibers, boron fibers, and ceramic fibers. Carbon fiber is one of the most widely used reinforcing fibers in structural applications (Karnati *et al.* 2020; Urtekin *et al.* 2022).

Carbon fiber fabrics have low density, superior tensile strength, modulus of elasticity, and fatigue properties. Due to this, they are widely used in different applications that require resistance to fatigue, bearing capacity of beams, and heat and sound insulation (Auriga *et al.* 2020). In recent years, carbon fiber fabrics have been commonly used for reinforcing LVL composite materials (Wei *et al.* 2013; Wang *et al.* 2015; Rescalvo *et al.* 2020; Perçin and Uzun 2022). A previous study by Rescalvo *et al.* (2022) tested some mechanical properties of poplar LVL reinforced with fiber-reinforced polymer (FRP). The obtained results showed a significant increase in the compressive and shear stiffness and elastic modulus for reinforced LVL samples. In another study, Bal (2014) studied the physical and mechanical properties of poplar LVL samples reinforced with glass fibers using phenol–formaldehyde (PF) adhesive. The test results indicated that density, impact bending, and shear strength increased. However, tangential swelling, volumetric swelling, moisture content, and specific impact bending decreased.

In recent years, users have been increasingly demanding wood material to have improved properties without the use of toxic chemicals. This desire has contributed to the increase in the popularity of heat-treated wood material. An effective method to improve some properties of wood material for efficiency can be done with the heat treatment method (Akyıldız and Ateş 2008). Wood heat treatment has increased significantly in the last few decades. The practice is continuing to grow as an industrial process to improve wood properties (Esteves and Pereira 2009), such as resistance to biodegradation and dimensional stability. Heat treatment further provides low hygroscopicity and equilibrium moisture content, a more attractive appearance, an increase in biological resistance to fungi and insects, and an increased resistance to weathering (Pelit *et al.* 2015). However, heat treatment causes undesirable changes in the wood material. Though thermal modification has been successful in improving dimensional stability and resistance against to wood-destroying fungi, it reduces mechanical properties in wood. The reduction in mechanical properties limits industrial applications, as the strength of wood is important. As a result, there is a trade-off between improved dimensional stability, increased resistance to biological attack, and decreased mechanical properties in application areas (Tiryaki 2015; Bayani *et al.* 2019).

Heat-treated wood is increasingly used in many applications such as garden, kitchen, and sauna furniture, cladding on wooden buildings, floor material, ceilings, doors, window joinery, and other outdoor and indoor applications (Jirouš-Rajković and Miklečić 2019). Due to some of its advanced properties, the demand for heat-treated wood continues to increase (Cao *et al.* 2022). However, due to deterioration in mechanical properties, the use of heat-treated wood as load-bearing structural material should be restricted (Nhacila *et al.* 2020). Therefore, the heat-treated wood used in the construction industry is expected to have great strength. In recent years, development in lamination technology has played an important role in the expansion of the use of laminated lumber (Korkut *et al.* 2008a).

The reinforcement of wood and structural wood products with different reinforcement materials and technique has been discussed many studies. However, most of them have focused primarily on the strengthening of low mechanical properties wood, the restoration, renovation, or strengthening of existing structures (Basterra *et al.* 2012). Fibers reinforcing materials, wood lamination technology, and thermally treatment have been widely used over the past few decades.

In recent years, the use of heat-treated wood material has been increasing. Studies on strengthening wood materials with low mechanical properties with synthetic fiber fabrics are widely carried out. However, the reinforcement of heat-treated LVL structural composites has not been reported in detail. For this reason, the aim of this study was to determine effects of the addition of carbon fiber fabric with different arrangements between heat-treated laminated veneer lumbers (LVL) bonded with polyurethane (PU) adhesive on air-dried density, MOR, and MOE of the manufactured composite samples.

EXPERIMENTAL

Materials

Wood material

Beech (*Fagus orientalis* Lipsky) lumber pieces (27 × 97 × 1500 mm) with an average moisture content of approximately 14% were provided from a local wood sawmill, Simav, in Kütahya, Turkey. Timber planks with a length of 450 mm and a nominal section of 25 × 95 mm were sawn for heat treatment. Planks had been stored for three weeks in a climate cabinet with relative humidity of 65 ± 5% and temperature of 20 ± 2 °C before heat treatment.

Carbon fiber

Carbon fibers were obtained from Dost Chemistry Industrial Raw Materials Industry and Trade Ltd. Co in Istanbul, Turkey. The product consists of a plain weave type Tenax-E HTA 40 3k yarn. According to data provided by the manufacturer, the tensile strength is 3800 MPa. It has a tensile modulus of 240 GPa, average density of 1.79 g cm^{-3}, tensile strain of 1.6%, carbon content in fiber of 95%, resin consumption of 234 gr/m^2, fiber diameter of 7 μm, and a laminate thickness of 0.327 mm.

Adhesive

Marine and Marine anti-aging adhesive was used as a binder. It is polyurethane-based (PU), one-component, and solvent-free product. It is a common adhesive used in the assembly and construction industry. The adhesive was obtained from Polisan Kansai Paint Industry and Trade Inc., in Turkey. The technical properties of the adhesive were as follows: density of 1.110 (g/cm^3), pH of 7.0 (at 25 °C), viscosity of 3000 to 5500 cPs (at 25 °C), and application amount of 200 (g m^{-2}).

Methods

Heat treatment

Beech planks were subjected to thermal treatment at temperatures of 150, 170, or 190 °C for 2 h in a small heating unit with an oxygen free atmosphere. The unit was a fully controlled oven with ± 1 °C sensitivity under atmospheric pressure. After heat treatment, beech samples were stored for a week for bonding process and veneers with a thickness of 4 mm and dimensions of 85 mm × 430 mm were cut from heat-treated and untreated planks using a circular saw machine. After sawing, veneers were conditioned at 20 ± 2 °C and 65 ± 5% relative humidity in a conditioning chamber to reach an equilibrium moisture content (EMC) of 12%.

Specimen preparation

In this study, the tests were carried out on five series of groups, one series of solid wood and the remaining four of LVL samples (Fig. 1).

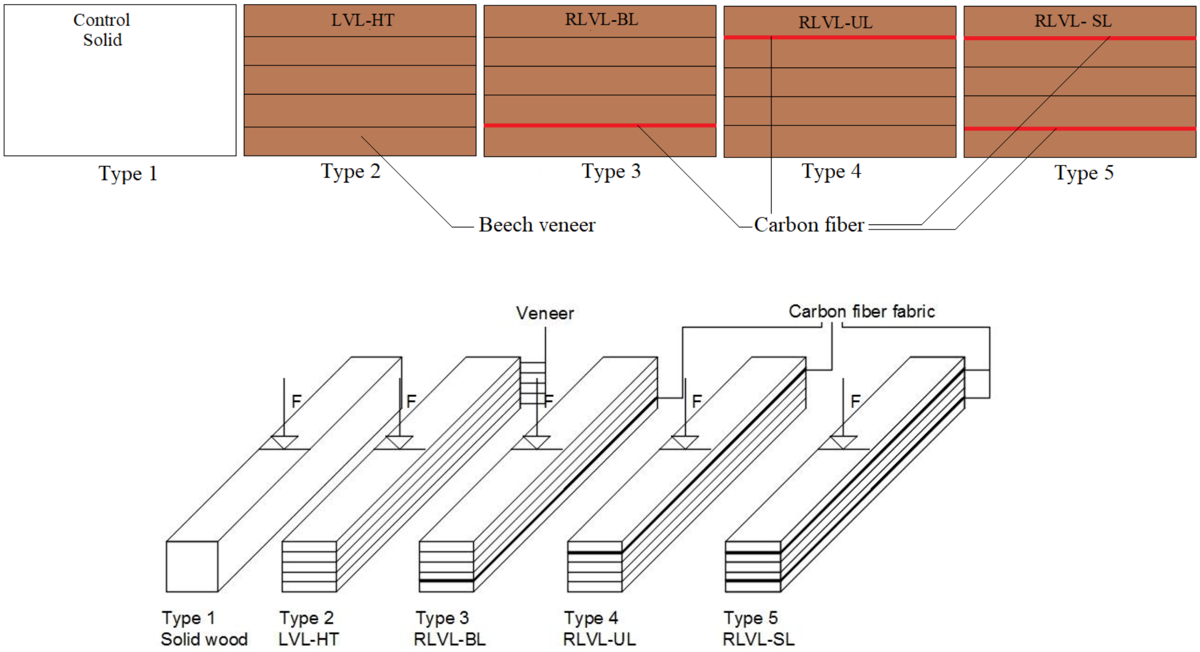

Fig. 1. Production of test samples

In this study, the properties of solid beech samples and heat-treated and reinforced beech LVL samples were compared. The manufactured LVL panels consisted of five veneers and carbon fiber fabric between them in different configurations. The first type of solid beech wood was the control group, while the second type (LVL-HT) was manufactured from five heat-treated veneers (no reinforcement with carbon fiber fabric was applied in this experimental group). The third type (RLVL-BL) consisted of five heat-treated veneers and one layer of carbon fiber fabric laid on the bottom adhesive line. The fourth type (RLVL-UL) was produced with five heat-treated veneers and one layer of carbon fiber fabric laid on the upper adhesive line. Finally, the fifth type (RLVL-SL) was produced with five heat-treated veneers and two carbon fiber fabric laid symmetrically on the bottom and upper adhesive lines. The adhesive spread was 200 g m^{-2} for veneer-to-veneer bonding and 300 g m^{-2} for each side of veneer-carbon fiber fabric bonding. Greater amount of adhesive was used due to the surface characteristics of the carbon fiber woven fabric. The pressing of all samples was made with a hydraulic press with a pressure of 10 N/mm^2 at 25 °C for 300 min. After the press process, the solid, LVL, and RLVL samples were stored for a week for exact curing. The air-dried density, bending strength (MOR), and bending modulus of elasticity (MOE) test samples were prepared according to the TS 2472 (1976), TS 2474 (1976), and TS 2478 (1976) standards. One hundred thirty test samples were prepared for each property: air-dried density, MOR and, MOE. In each experimental group, ten specimens were prepared to reduce the variability of results. The manufactured samples were conditioned at a temperature of 20 ± 2 °C and 65 ± 5% relative humidity for three weeks before tests. All mechanical tests were performed using a Universal Test Machine (Instron-5969) with 4 mm/min loading speed. The workflow showing the production process is given in Fig. 2.

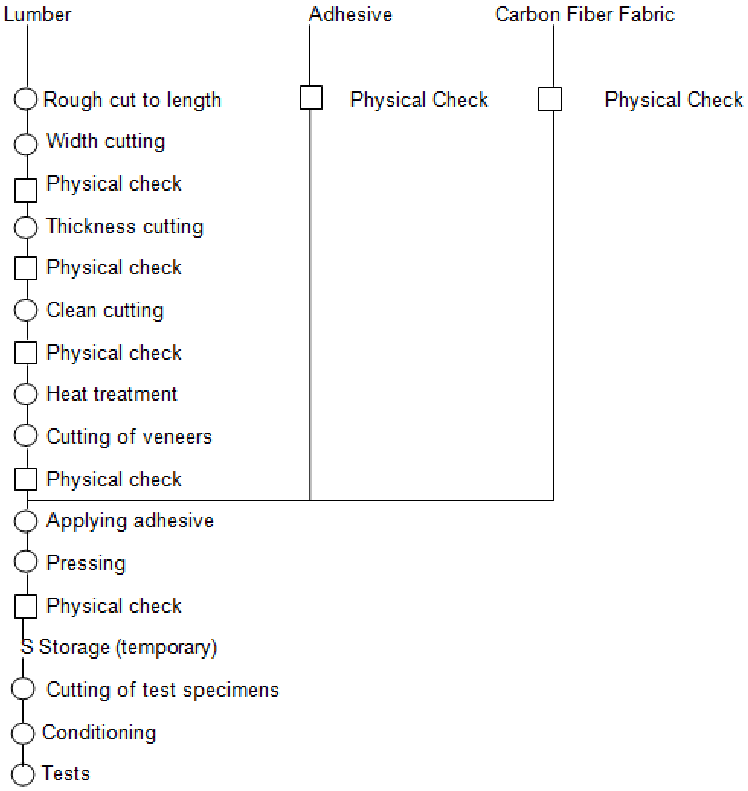

Fig. 2. The workflow showing in the production process

Statistical analyses

The MSTAT-C software package (Michigan State University, USA) was used for the statistical analysis of the data. It was used to show the effect of heat treatment and reinforcement on bending strength of beech wood. Analysis of variance (ANOVA) was performed to determine whether there were any significant differences among the experimental samples. ANOVA followed by Duncan's test with 0.05 significance level was used to show significant differences.

RESULTS AND DISCUSSION

The mean density values of beech solid and LVL samples at 20 °C and 65% relative humidity are summarized in Table 1. The mean density value of the solid sample was 0.691 g cm^{-3}. Density values at 150 °C ranged from 0.713 to 0.733 g cm^{-3}, whereas at 170 °C they were from 0.672 to 0.694 g cm^{-3}. At 190 °C, the values ranged from 0.653 to 0.675 g cm^{-3}. The density decreased with increasing treatment temperature. The density values of RLVL-BL, RLVL-UL, and RLVL-SL were higher than those of LVL-HT. This occurred due to the greater amount of adhesive applied in the reinforced samples and the high-density carbon fiber. The increase in density of the LVL by the reinforcements of carbon fibers is consistent with the literature (Basterra *et al.* 2012; Wei *et al.* 2013). Reduction of density values can be mainly attributed to the thermal degradation of wood chemical components. The density of the heat-treated samples decreased due to the degradation of cell wall components and mass losses during the heat treatment (Boonstra *et al.* 2007; Zhou *et al.* 2020).

Table 1. Density Values of Heat-Treated Beech Solid and LVL Samples Reinforced with Carbon Fiber Fabric

Heat Treatment	Reinforcement Type	Mean (g cm^{-3})	Homogenous Groups	Standard Deviation (g cm^{-3})	Minimum (g cm^{-3})	Maximum (g cm^{-3})
Control	Solid	0.691	E	0.00641	0.685	0.699
150 °C	LVL-HT	0.713	C	0.00681	0.701	0.726
	RLVL-BL	0.723	B	0.00798	0.710	0.740
	RLVL-UL	0.722	B	0.00634	0.710	0.733
	RLVL-SL	0.733	A	0.00539	0.722	0.741
170 °C	LVL-HT	0.672	H	0.00579	0.663	0.681
	RLVL-BL	0.682	F	0.00641	0.670	0.691
	RLVL-UL	0.683	F	0.00710	0.678	0.687
	RLVL-SL	0.694	D	0.00627	0.689	0.699
190 °C	LVL-HT	0.653	J	0.00594	0.647	0.659
	RLVL-BL	0.664	I	0.00585	0.659	0.669
	RLVL-UL	0.663	I	0.00485	0.657	0.669
	RLVL-SL	0.675	G	0.00545	0.669	0.679

Different letters show which values are statistically different at the 0.05 level whereas same letters means there was no significant effect.

The average bending strength values according to heat treatment temperature and reinforcement type are summarized in Table 2 and Fig 3.

Table 2. Mean Comparison of MOR Values in Heat Treatment and Reinforcement Type Level

Heat Treatment	Mean (N mm^{-2})	Homogenous groups
Control	101.4	B
150 °C	103.0	A
170 °C	96.08	C
190 °C	85.73	D
Reinforcement type		
LVL-HT	95.19	D
RLVL-BL	97.37	B
RLVL-UL	95.86	C
RLVL-SL	97.87	A

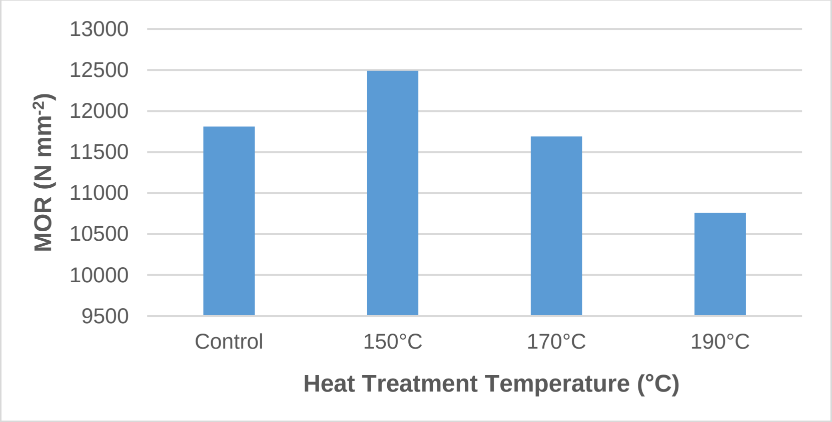

Fig. 3. The average bending strength values according to heat treatment temperature

According to Table 2 and Fig. 3, the results show that the MOR of heat-treated samples generally exhibited a decrease with increasing treatment temperature relative to the control group. The MOR increased at the initial stage of the heat treatment and decreased later. It decreased heat-treated samples at 190 °C more. For mild treatment conditions, the MOE often increases but decreases with severe treatment conditions (Militz and Altgen 2014). The initial increase of MOE can be attributed to an increase in the crystallinity of cellulose and a decrease in the equilibrium moisture content of wood (Esteves and Pereira 2009). Shi *et al.* (2007) studied the mechanical behavior of heat-treated wood samples using a Thermowood process. They reported that the MOR decreased for heat-treated spruce, pine, fir, and aspen. For birch, however, the MOR increased slightly after the heat treatment. The lowest MOR value of samples was 85.73 N mm^{-2} at 190 °C and the highest was 105.3 N mm^{-2} at 150 °C. This deterioration occurred because of hemicellulose degradation. Yildiz *et al.* (2006) reported that hemicelluloses were the most degraded wood-cell components at high heat treatment temperature. In general, the results of this study on the effect of heat treatment on MOR properties are compatible with the findings in the literature (Poncsak *et al.* 2006; Korkut *et al.* 2008b; Kocaefe *et al.* 2010).

Table 2 shows that the MOR values of the RLVL-BL, RLVL-UL, and RLVL-SL were higher than the LVL-HT samples by 3%, 1%, and 4%. While the highest increase was determined in RLVL-SL, the lowest was in RLVL-UL. Although the effects of reinforcement types on MOR were close to each other, this difference was statistically significant. A better reinforcement effect was obtained when two carbon fibers were laid symmetrically on the bottom and upper adhesive lines. The increase in RLVL-SL was slightly higher than RLVL-BL with the two-layer reinforcement process. By comparison, RLVL-BL had a higher MOR value than the RLVL-UL. In other words, higher MOR was obtained in the reinforcements made at the bottom glue line, in a single-layer reinforcement process. The increased MOR value of reinforced bottom layer by the reinforcements of carbon fibers is consistent with the literature (Wei *et al.* 2013; Wang *et al.* 2015). Although the reinforcement effect of carbon fiber fabric was lower than those in the literature, some researchers reported that the mechanical properties of composites improved significantly. Auriga *et al.* (2020) reported that carbon fiber fabrics placed near the external veneers for parallel direction of plywood panels showed higher reinforcement effect. In addition, similar results have been reported in other literature (Wang *et al.* 2015; Liu *et al.* 2019).

Table 3 shows variance analysis results for the MOR of the heat-treated and reinforced beech samples.

Table 3. Analysis of Variance Results for MOR Values

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	P<0.05 Sig.
Factor (A)	3	7330.503	2443.501	1960.1808	0.0000
Factor (B)	3	189.530	63.177	50.6803	0.0000
A x B	9	71.975	7.997	6.4154	0.0000
Error	114	179.506	1.574		
Total	129	7771.514			

Factor A: Heat treatment temperature (150, 170 and 190°C); Factor B: Reinforcement type (RLVL-BL, RLVL-UL and RLVL-SL); Degrees of freedom: In degrees of freedom statistics, when a statistic is obtained precisely, taking into account the values used gives the freedom numerically.

According to variance analysis results, heat treatment and reinforcement as well as dual interaction of these factors on the MOR values were significant ($P \leq 0.05$). Figure 4 shows the MOR values of beech samples. Different changes were observed in the MOR values after heat treatment and reinforcement process. The increase in temperature of the heat treatment decreased the MOR values. On the other hand, the MOR values of all heat-treated and reinforced samples were higher than those of the heat-treated and non-reinforced samples under the same conditions. The reinforcement process had a significant effect on MOR. With the reinforcement with carbon fiber, an increase in the mean MOR values for reinforced LVL when compared to heat treated LVL-HT under the same conditions occurred.

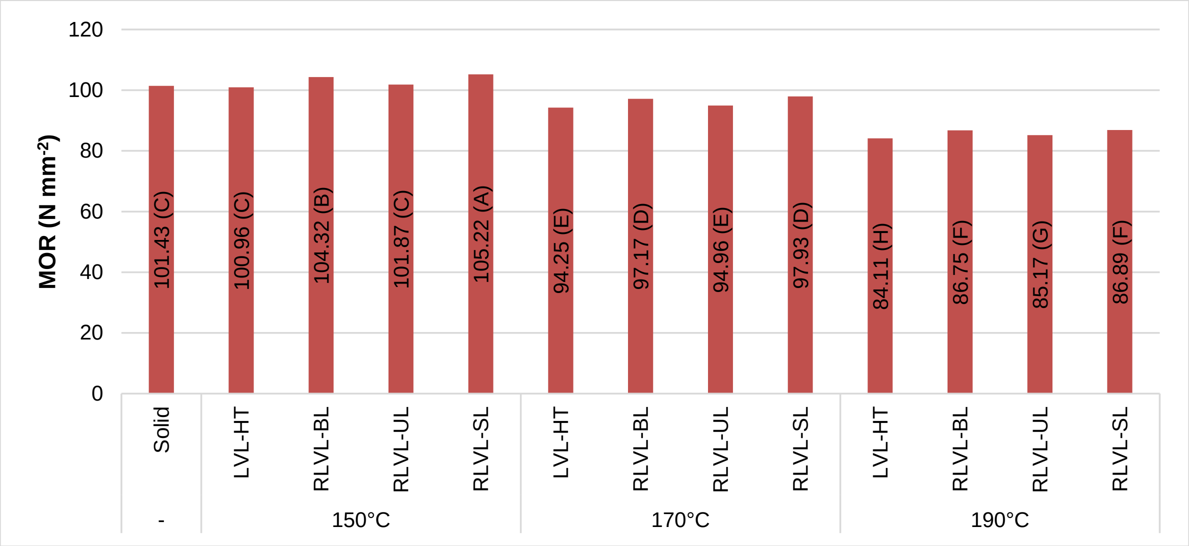

Fig. 4. Comparative appearance of MOR values in beech samples

The MOE values of beech samples according to heat treatment temperature and reinforcement type are presented in Table 4 and Fig. 5. The modulus of elasticity (MOE) increased slightly for wood treated at 150 °C. Heat-treated samples at 190 °C gave the lowest values compared to the control group, reaching an 8.8% decrease after treatment. Esteves and Pereira (2009) reported that the MOE can increase slightly at low temperatures but decrease as treatment conditions become severe. This improvement in mechanical properties can be attributed to a significant increase in the degree of crystallinity of the wood and cross-linking in lignin (Bayani *et al.* 2019).

Table 4. Mean Comparison of MOE Values in Heat Treatment, and Reinforcement Type Level

Heat Treatment	Mean (N mm^{-2})	Homogenous Groups
Control	11810	B
150°C	12490	A
170°C	11690	C
190°C	10760	D
Reinforcement type		
LVL-HT	11210	D
RLVL-BL	11920	B
RLVL-UL	11490	C
RLVL-SL	12170	A

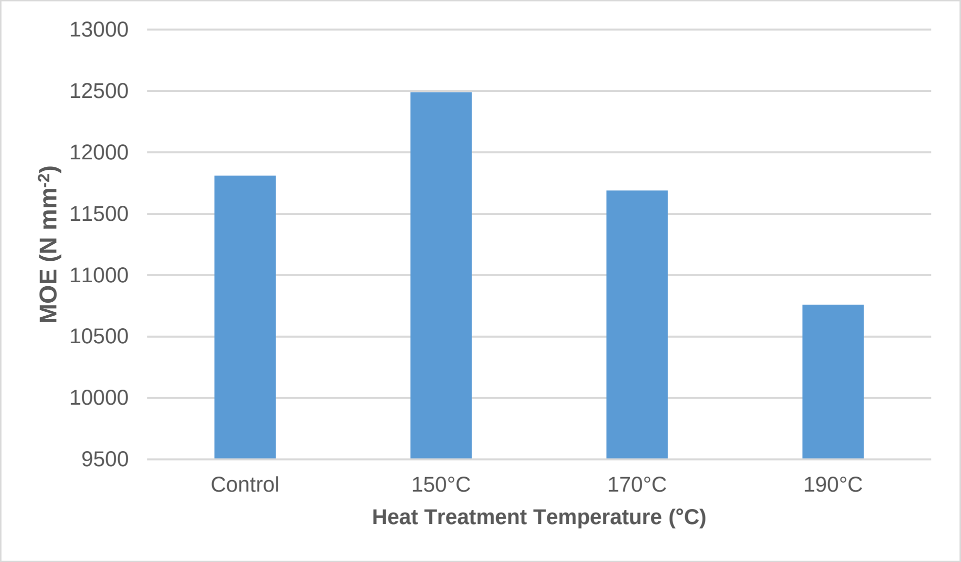

Fig. 5. The MOE values of beech samples according to heat treatment temperature

An increase of MOE was observed for all LVL made with the addition of carbon fibers compared to the unreinforced LVL (LVL-HT). It was determined that the MOE values of the RLVL-BL, RLVL-UL, and RLVL-SL were higher than the LVL-HT samples by 6%, 2% and 8%. From Table 2 and Table 4, the increase in MOE values of reinforced samples was higher than the increase in MOR values. During the bending strength test, after the test starts, a tensile force was generated from the areas close to the bottom surface of the test specimen towards the support points. As a result, the MOR and MOE values were slightly higher in the samples with carbon fiber fabric added. In the previous studies on reinforcement materials, it was determined that the reinforcement materials adhered to the lower surface of the test sample or used in the intermediate glue layer increased the mechanical properties (Biblis and Carino 2000; Bal *et al.* 2015). A similar study was conducted by Bal and Özyurt (2015), who reported that the reinforcing fabric significantly increased the MOE values of poplar LVL. However, there was no significant increase in MOR values.

Variance analysis results for the MOE of the heat-treated and reinforced beech samples are given in Table 5. According to variance analysis results, heat treatment and reinforcement as well as dual interaction of these factors on the MOE values were significant ($P \leq 0.05$). The MOE values of beech samples are presented in Fig. 6.

Table 5. Analysis of Variance Results for MOE Values

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	P<0.05 Sig.
Factor (A)	3	61142161.875	20380720.625	637.3958	0.0000
Factor (B)	3	22800966.875	7600322.292	237.6959	0.0000
A x B	9	8334675.625	926075.069	28.9625	0.0000
Error	114	4604398.000	40389.456		
Total	129	96882202.375			

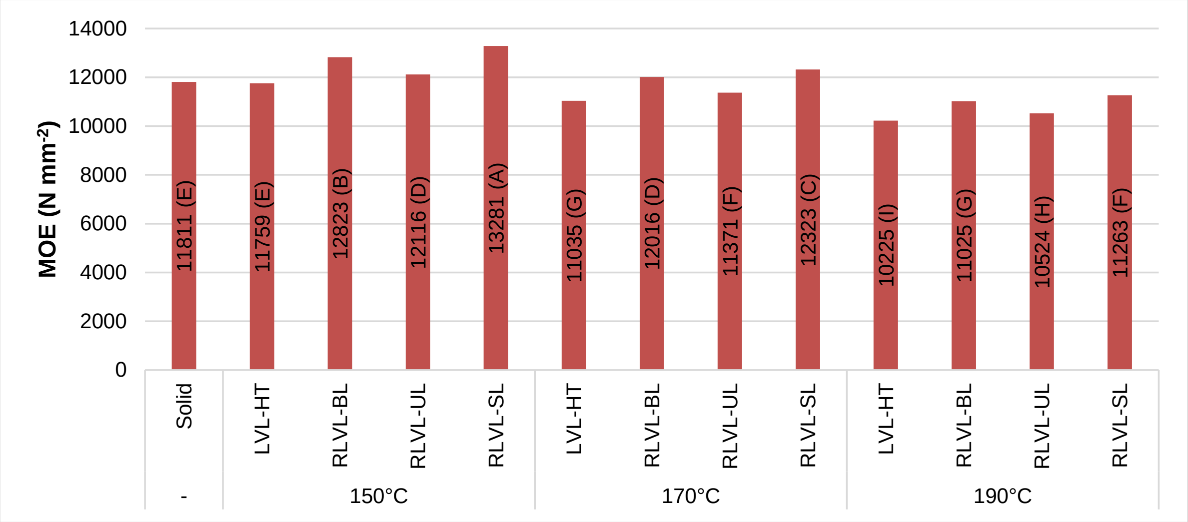

Fig. 6. Comparative appearance of MOE values in beech samples

A similar variability was observed for the modulus of elasticity. After heat treatment under the same conditions, the MOE values of heat-treated and reinforced samples were higher than unreinforced (LVL-HT). Therefore, the reinforcement of LVL with carbon fiber fabric increased the MOE values in all heat treatment conditions. A statistical difference was found between the results of the reinforced and unreinforced laminated samples. In this study, the MOR and MOE values of the reinforced samples were higher than the non-reinforced samples. It is thought that this is due to the increase in the density values of the reinforced samples and the good adhesion between the heat-treated beech veneers and the carbon fiber fabric. The increase in strength of the LVL by the reinforcements of carbon fibers is consistent with the literature. In a similar study, Percin and Altunok (2017) tested some physical and mechanical properties of heat-treated LVL reinforced with carbon fibers using Desmodur-VTKA (DVTKA) adhesive. The obtained results showed a significant increase in the MOE value for reinforced LVL samples. In addition, Cibo *et al.* (2018), Bakalarz and Kossakowski (2019), and Çiğdem and Perçin (2023) noted similar results for MOE.

CONCLUSIONS

1. The effects of reinforcement with carbon fiber fabric on some mechanical and physical properties of laminated veneer lumber (LVL) produced from heat-treated beech veneer bonded by polyurethane (PU) adhesive were investigated. Findings indicated that density changed significantly, and an increase of density was observed for all heat-treated LVL made with the addition of carbon fiber fabric compared to the unreinforced LVL (LVL-HT).
2. In this study bending tests were applied to flatwise direction, and the values of modulus of rupture (MOR) and modulus of elasticity (MOE) decreased with heat treatment temperature. However, the MOR and MOE values of all heat-treated fabric-reinforced laminated veneer lumber (RLVL) increased more than those for LVL. This increase was greater in the RLVL-SL than in the RLVL-BL and RLVL-UL versions. On the other hand, the increase in RLVL-SL was slightly higher than RLVL-BL with a two layer reinforcement process.
3. Concerning the effect of one layer carbon fiber fabric on the MOR and MOE of heat-treated samples, it was revealed that these mechanical properties of RLVL-BL were higher than for the RLVL-UL. Laying the carbon fiber fabric close to the bottom layer contributed to a greater increase in MOR and MOE. Further studies should be performed with other materials such as different reinforcements (glass fiber, kevlar or aramid fiber, and natural fiber), fast growing low quality woods, various wood species that have been heat-treated under different conditions, and different adhesives.

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