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ORIGINAL ARTICLE

# Influence of carbon fibre layers on the strength of thermally modified laminated veneer lumber

**Osman Perçin[1]* and Onur Ülker[2]***

*[1]Department of Interior Architecture and Environmental Design, Faculty of Fine Arts and Architecture, Necmettin Erbakan University, Meram, Konya, Turkey*

*[2]Department of Interior Architecture, Faculty of Architecture and Design, Eskisehir Technical University, Tepebasi, Eskisehir, Turkey*

**onurulker@eskisehir.edu.tr*

## Abstract

Thermally modification of wood is an environment-friendly alternative method for improving several properties of wood without the use of chemicals. The compressive strength (CS) parallel to the grain of reinforced laminated veneer lumber (LVL) manufactured from heat treated beech (*Fagus orientalis*) veneers and carbon fibre was determined. Thermally modification was performed at 140°C, 160°C, 180°C, and 200 °C according to thermal treatment process. Carbon fibre were added as a reinforcement layer between wood veneers bonded with phenol-formaldehyde (PF), polyvinyl acetate (PVAc) polyurethane adhesives (PU) to improve properties of LVL. Results showed that reinforcing LVL panels with carbon fibre increased both density and CS. The PF adhesive showed better results for reinforced LVL panels with carbon fibre. The anatomical structure and density of the wood material significantly affect its mechanical properties, including compressive strength parallel to the grains. Wood density had a strong significant linear relationship with CS.

**Keywords:** *laminated veneer lumber, carbon fibre, thermal treatment process, beech.*

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## 1. Introduction

Wood material is one of the earliest building and engineering materials used by mankind in the world. It continues to be a remarkable material in the construction and woodworking industries. Wood has unfavorable structural features as knots, combustion properties, dimensional instability, low biological resistance, easy degradation from external environmental conditions, and twisted fibres[1,2]. It is necessary to improve or eliminate these unfavorable structural features of wood material and make it suitable for its end use.

In recent years, considering the environment and human health, different methods have been developed to eliminate or minimize the unfavorable properties of wood and wood-based materials. One of the most popular methods is thermal modification, and its application is increasing in recent years[3-5]. Thermal modification has been found to be an effective method to improve wood dimensional stability, biological durability, and to reduce the equilibrium moisture content. Thermal modification alters the cell wall polymer and chemistry of wood by heating at high temperature levels. High temperature changes the chemical and anatomical properties of wood[6,7]. Furthermore, mechanical strength properties may also decrease depending on the treatment conditions[8-11].

In the last couple of decades, there has been a rapid increase in the consumption of forest resources due to increase in the world population, increase in the demand for wood materials, unsustainable use of forest resources, forest fires, and natural disasters such as landslides. Structural composite timbers (SCLs) have been produced to eliminate the structural defects of the wood material and to use wood material more efficiently. One of these structural composite timbers is laminated veneer lumber (LVL); it is one of the most widely used high- strength engineered wood products for constructional applications that is also an alternative to solid wood used for structural applications[12,13].

Structural composite lumber can be reinforced with synthetic fibres to effectively improve their structural properties. The commonly used fibre reinforced polymer (FRP) composite for wood is glass-fibre reinforced polymer (GFRP), aramid fibre reinforced polymer (AFRP), carbon-fibre reinforced polymer (CFRP), and hybrid materials (carbon fibres and glass fibres)[14-21]. Glass fibre fabrics have lower resistance properties to alkaline environments and lower fatigue strength. Aramid fibres have closely strength properties to glass fibres but are more resistant to fatigue. Alternatively, carbon fibres are characterized by higher stiffness than glass fibres and they are more stable against chemicals and high temperatures. Also, these fibres have the best properties among fibres used in the production of fibre composites[8].

Over the years, to improve of technological properties of LVL as a construction material, reinforcement of LVL,

wood and adhesive type and methods have been carried out by many researchers[22-33]. When previous studies are analyzed, many of the researchers have been focused effect of reinforcement material on tension of glulam or timber in bending, modulus of rupture (MOR), and modulus of elasticity (MOE), however reinforcing LVL has not been commonly reported. In addition, the use of heat-treated wood material both indoors and outdoors is increasing, and an increase is observed in the demand for heat-treated wood material in the woodworking industry.

Thermal modification significantly reduces some mechanical properties, including the compressive strength parallel to the grains, however the dimensional stability and the biological durability of wood increases after heat treatment process. Compression strength of wood and wood composites materials plays an important role in almost any construction applications[34-36].

Hence, the objective of this study was to determine the influence of carbon fibre reinforcement on compressive strength parallel to the grain of laminated veneer lumber (LVL) bonded with phenol-formaldehyde (PF), polyvinyl acetate (PVAc) (all the resins used separately) and polyurethane adhesives (PU) using heat-treated beech (*Fagus orientalis* Lipsky) veneers.

## 2. Materials and Methods

Beech (*Fagus orientalis*) wood is one of the widespread tree species in the World to use in LVL. Beech (*Fagus orientalis*) wood was investigated herein because of its wide usage in the wood working and construction industry[37]. Defect-free draft samples (20mm×750mm×100mm) were subjected to heat treatment. Thermally modification was done under a controlled environment with heat tolerance of ±0.1°C. Thermally modification of the test samples was carried out in three stages (drying at high temperature, heat treatment, cooling, and conditioning) given in Figure 1. In the first stage, the temperature was raised to 100°C for 5 hours, then to 130°C for 10 hours, and then to the target temperature for 5 hours. In the second stage, heat treatment has been applied in the aimed four different temperatures (140°C, 160°C, 180°C and 200°C) for two hours. During stage I and II, steam was applied for 5 seconds at 200°C second intervals. In the third stage, the temperature was decreased to room temperature (20±2°C). The total thermally modification period took 35 hours for each temperature value. After the heat treatment process, the samples were rested in a suitable place under atmospheric conditions for three weeks. There are 7 groups (solid wood beech, PVAc-LVL, PF-LVL, PU-LVL, PVAc-RLVL, PF-RLVL, PU-RLVL) researched, in each group 5 different temperatures

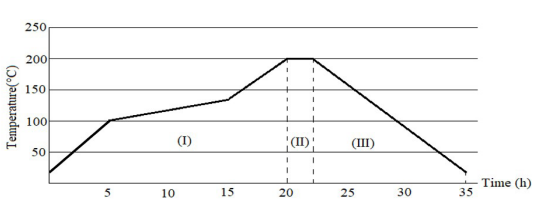


**Figure 1.** Schematic representation of heat treatment process.

investigated, control 20°C, heat treatment groups 140°C, 160°C, 180°C, 200°C. Totally 350 test samples prepared for mechanical tests.

Many chemical and physical properties of wood are permanently altered by the heating process. The main reason for using the features is the thermal degradation of the half-cells. The desired changes become apparent from about 150 ºC and continue with the stairs as the temperatures of the temperature. Esteves and Pereira published a review about wood modification and heat treatment, they cite 163 publications about heat treatment. In major publications, heat treatment applications were changed from 140°C to 200°C[38]. As a result, moisture rise, and shrinkage fall; biological endurance increases; is the color decision; splitting a large number of decomposing substances flowing through the wood; wood becomes lighter; decrease in equilibrium moisture content; The pH value decreases, and the thermal gloss properties become better.

In this study, 200 gr/m$^2$ plain weave carbon fibre was used as reinforcing materials. Carbon fibres were obtained from Dost Kimya Inc., Istanbul, Turkey. According to the technical data provided by the manufacturer, the tensile strength is 3800 MPa, tensile modulus 240 GPa, average density 1.79 g/cm$^3$ and tensile strain 1.6%.

Polyvinyl acetate (PVAc), phenol-formaldehyde (PF), and polyurethane adhesives (PU) were used as binder. The PVAc and PU adhesives were supplied by POLISAN firm. City, Turkey. PVAc adhesive density is 1.1 g/cm$^3$, viscosity 16.000±3.000 mPa s, and pH 5. PF adhesive was purchased from Gentas Company, Bolu, Turkey. It has a density of 1.12 g/cm$^3$ at 20 °C, pH 8.4, viscosity 600 cPs at 20 °C, and contains solid matter at 48%[4]. PU adhesive has an approximate pH of 7 and a viscosity of 5500-7500 mPa at 25°C. Its density is 1.11±0.02 g/cm$^3$, and the period of solidification at 20°C and 65% relative humidity is 24 h, as specified by Gentas Company, Bolu, Turkey.

Thermally modificated veneers were used in the LVL composites manufacturing. Before producing LVL composites, heat-treated draft samples were cut in the dimension of 4 × 70 × 700 mm (radial direction × tangent direction × longitudinal direction). Conditioned at 20±2°C, and 65±%5 relative humidity for at least three weeks. The lamination process of the test samples was carried out under laboratory conditions at room temperature (20 ±2°C). In this process, the adhesives were applied on one surface of the veneers and both sides of the carbon fibre fabric. They were 180 g/m$^2$ for veneer-veneer bonding and 250 g/m$^2$ for veneer-carbon fibre bonding. The surface characteristics of the carbon fibre fabric were effective to permit in spreading the high amount of adhesive to compensate the weaker bonding properties of the adhesive to the carbon fibre compared to wood samples. The hydraulic pressing of all samples was made with a pressure of 10 N/mm$^2$ and temperature of 130 °C during 30 min for PF, 22 °C during 240 min for PU and 22 °C during 240 min for PVAc, and all the panels were stored for 10 days for curing (The stocks were removed from the hydraulic press and kept in a closed environment for a period of 10 days). After the curing process, 15 mm edges were trimmed off from the panels, and test samples were

then machined. The manufacturing process of test samples are depicted in Figure 2.

The compressive strength parallel to grain (CS) was determined using a universal testing machine (Instron-5969) according to the ISO 13061-17 (2017) standard[39]. The dimensions of the test samples were 20 mm × 20 mm × 30 mm and during tests the loading rate was 2.5 mm/min. Ten samples were prepared in each experimental group. Figure 3 depicts the test setup for compressive strength parallel to grain test. Specimens were conditioned in a conditioning chamber at temperatures of 20 ±2 °C and relative humidity of 65 ±5% until reached constant weight before the mechanical test. After the climatization process, the mass of each specimen (*M*) and volume (*V*) were determined. The air-dry density (*D*) of the specimens was determined according to ISO 13061-2 (2014)[40] and calculated using Equation 1:

$$D\left(g\ mm^{-3}\right) = M\ /\ V \quad (1)$$

The CS value was calculated by using Equation 2:

$$CS\left(N\ mm^{-2}\right) = P_{max}\ /\ b.d \quad (2)$$

where $P_{max}$ is the maximum load applied to the specimens (N), b is the width of the specimens (mm), and d is their thickness (mm).

Analysis of variance (ANOVA) tests were performed to determine the effect of thermal treatment temperature, carbon fibre fabric and adhesive types on the compressive strength parallel to grain of beech wood at the 0.05 significance level. Significant differences between the average values of the groups were compared using Duncan's test by using the Least Significant Difference (LSD) value.

## 3. Results and Discussions

In Table 1, the mean values of the specimens density are listed. The density value of three types of reinforced LVL were higher than that both unreinforced LVL and solid woods groups. The highest density was 776 kg/m$^3$ for the reinforced specimens bonded with PF adhesive control group. Increases in density can be explained by the greater amount of adhesive spread in the reinforced samples and the higher density of the carbon fibre fabric regarding the base materials. Wei et al.[41] evaluated the effect of carbon fibre reinforced polymer LVL. The authors reported that the reinforcing process increased the density value of test samples. Also, Auriga et al.[17] reported that density of the reinforced samples with carbon fibres was higher than the control group. Density of wood and wood-based composites are one of the most important properties that affect other physical and mechanical properties, and it is commonly considered as the predictor of strength properties[42], in


**Figure 2.** The manufacturing process of test samples.

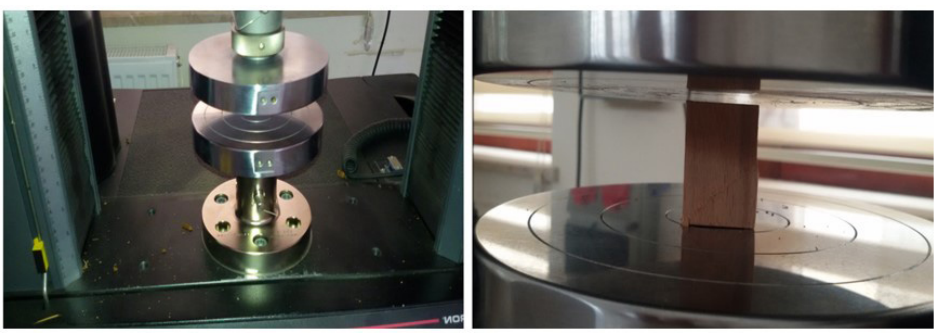

**Figure 3.** Test setup for compressive strength parallel to grain.

**Table 1.** The density values of LVL and RLVL (reinforced LVL) samples.

| Group of Samples | Heat Treatment (°C) | Density (g mm$^{-3}$) (Mean value) | Min (g mm$^{-3}$) | Max (g mm$^{-3}$) | SD (Standard Deviation) | Changes (%) |
|---|---|---|---|---|---|---|
| Solid Wood beech (*Fagus orientalis*) | Control | 0.691 | 0.655 | 0.731 | 0.025 | - |
| | 140 | 0.684 | 0.657 | 0.719 | 0.017 | -1.02 |
| | 160 | 0.672 | 0.653 | 0.698 | 0.016 | -2.83 |
| | 180 | 0.663 | 0.639 | 0.697 | 0.015 | -4.22 |
| | 200 | 0.648 | 0.614 | 0.683 | 0.020 | -6.64 |
| PVAc-LVL | Unheated | 0.717 | 0.685 | 0.751 | 0.020 | 3.63 |
| | 140 | 0.707 | 0.675 | 0.733 | 0.017 | 2.26 |
| | 160 | 0.693 | 0.668 | 0.711 | 0.015 | 0.29 |
| | 180 | 0.684 | 0.645 | 0.722 | 0.025 | -1.02 |
| | 200 | 0.673 | 0.631 | 0.699 | 0.000 | -2.67 |
| PF-LVL | Unheated | 0.727 | 0.708 | 0.748 | 0.014 | 4.95 |
| | 140 | 0.716 | 0.681 | 0.755 | 0.024 | 3.49 |
| | 160 | 0.706 | 0.673 | 0.745 | 0.021 | 2.12 |
| | 180 | 0.695 | 0.676 | 0.723 | 0.016 | 0.58 |
| | 200 | 0.685 | 0.668 | 0.707 | 0.013 | -0.88 |
| PU-LVL | Unheated | 0.715 | 0.679 | 0.724 | 0.014 | 3.36 |
| | 140 | 0.711 | 0.685 | 0.739 | 0.019 | 2.81 |
| | 160 | 0.694 | 0.663 | 0.749 | 0.023 | 0.43 |
| | 180 | 0.686 | 0.652 | 0.721 | 0.021 | -0.73 |
| | 200 | 0.675 | 0.649 | 0.695 | 0.016 | -2.37 |
| PVAc-RLVL | Unheated | 0.753 | 0.732 | 0.775 | 0.015 | 8.23 |
| | 140 | 0.744 | 0.698 | 0.779 | 0.025 | 7.12 |
| | 160 | 0.731 | 0.676 | 0.763 | 0.026 | 5.47 |
| | 180 | 0.721 | 0.673 | 0.759 | 0.027 | 4.16 |
| | 200 | 0.713 | 0.665 | 0.743 | 0.028 | 3.09 |
| PF-RLVL | Unheated | 0.776 | 0.739 | 0.799 | 0.019 | 10.95 |
| | 140 | 0.763 | 0.747 | 0.789 | 0.012 | 9.44 |
| | 160 | 0.752 | 0.715 | 0.779 | 0.019 | 8.11 |
| | 180 | 0.742 | 0.699 | 0.773 | 0.025 | 6.87 |
| | 200 | 0.733 | 0.681 | 0.769 | 0.024 | 5.73 |
| PU-RLVL | Unheated | 0.754 | 0.705 | 0.776 | 0.020 | 8.36 |
| | 140 | 0.748 | 0.721 | 0.766 | 0.015 | 7.62 |
| | 160 | 0.729 | 0.695 | 0.769 | 0.024 | 5.21 |
| | 180 | 0.722 | 0.685 | 0.751 | 0.023 | 4.29 |
| | 200 | 0.712 | 0.688 | 0.745 | 0.019 | 2.95 |

Figure 4, seven groups of specimens density and heat treatment groups illustrated.

In this study, density values of reinforced and unreinforced LVL specimens varied significantly. According to Table 1 heat treatment significantly reduces the density of specimens as the applied temperature is increased, regardless of the material tested. The largest reduction on the density of *Fagus orientalis* were -4.22% at the 180°C and -6.64% at the 200 °C. It is well known that the heating of wood significantly changes its physical and mechanical properties due to degradation of hemicelluloses[39,43,44] which is proportional to the applied temperature.

Density values of samples were heavily dependent on properties of the adhesives used and press conditions. When the density values were compared, the density values of the samples laminated with PF glue were higher than the density values of the samples laminated with the other two glues. This may have been due to the difference in the pressing process with PF glue. In the pressing process with PF glue, a small mechanical condensation process may have occurred here, since temperature is applied along with press pressure. This may have led to an increase in the density values of the samples laminated with PF glue. This situation can be explained by the distinct structural properties of the PF

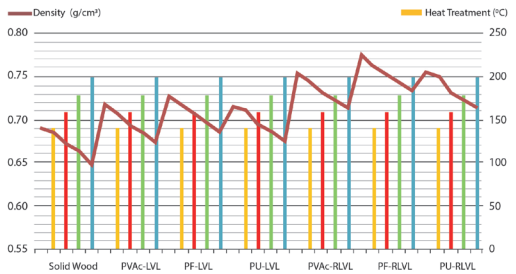


**Figure 4.** Density values according to heat treatment at solid wood, LVL and RLVL samples.

adhesive itself and the laminate production process. In the lamination process with PF adhesive, the press temperature was applied as 130 °C and the press time was 30 min. On the other hand, PVAc and PU adhesives were also applied at a temperature of 25 °C and press time 240 min. The press pressure was 10 N $mm^{-2}$ in the production of all samples. Lamination process beech veneers glued with PF resins at hot pressure may have caused thermo-mechanical densification and consequently this situation may have been caused an increase in samples density[45].

In recent years, interest in thermal modification of wood and reinforced wood composite materials have been increasing and its use in structural applications is increasing[17,45-51]. It is a widely known fact that heat treated wood material can be more brittle than unheated wood and prone to cracking. Due to the increased brittleness of heat-treated wood material and important to determine the fracture properties if it is used in structural applications particularly fracture in tension perpendicular to the grain[52,53].

In the present study, failure types of solid wood and laminated veneer lumbers in compression parallel to grain were significantly changed after heat treatment. Compared with the unheated samples, delamination of adhesive layer and fracture type of specimens at maximum compressive load of heat-treated sample was much more serious and different. Fracture occurred abruptly at maximum load in samples that were thermally modificated at 180°C and 200°C while non-modified specimens were plastification before failure.

The three most common failure modes are depicted in Figure 5. The failure caused by shearing is presented in Figure 5a. splitting and shearing failure is depicted in Figure 5b and crushing, and splitting failure is illustrated in Figure 5c de la Rosa García et al.[54] stated that the fracture toughness of thermally modified of wood material is not only dependent on the density, but also depend on the temperature, changes in the internal structure of wood and the degree of degradation of the cell wall components. Also, Sebera et al.[42] reported the fracture properties of heat-treated beech wood should be taken into consideration for structural application, when cyclic loading may lead to microcracking and material fatigue.

Table 2 shows the effects of reinforcement on the compressive strength parallel to the grains (CS) and Duncan test results of LVL and RLVL laminates. It has been shown that the effect of adhesive type, and carbon fibre fabric on the compressive strength parallel to the grains was significant ($p<0.05$). An increase of CS was observed for all samples made with the addition of carbon fibre compared to the unreinforced and solid wood groups. Also, Table 2 shows that the CS decreases significantly with thermal treatment. It appears that the heat treatment, type of adhesive and reinforcement influence the CS differently. After reinforcement process of heat-treated and unheated samples, the CS improved greatly. The values of the CS of the reinforced samples are significantly higher from 1.02% to 24.27% than those of the control samples. Based on the findings in this study, the results showed that CS values increased at low temperatures, while it decreased with increasing treatment temperature. According to Table 2, CS values varied largely.

Average CS of the samples varied from 64.21 $Nmm^{-2}$ (200°C) to 90.61 $Nmm^{-2}$ (160°C). While the CS values increased at low temperatures, they decreased as the temperature increased in all the test groups. The maximum decrease and increase percentages of CS were 6.83% (200°C) and 24.27% (160°C), respectively. Increase in compressive strength parallel to the grain at low temperatures can be explained by the decrease in moisture content due to the increase in cellulose crystallinity[18], while the significant decrease in CS values at high temperatures can be explained by the chemical change and degradation of chemical compounds of the wood material[39]. Average CS values of the test samples in solid wood group agree with the literature[55]. In addition, Boonstra et al.[34] evaluated the influences of high temperatures (ranging from 150 to 260°C) on the mechanical properties of wood material and stated that heat treatment increased CS values of samples.

As shown in Table 2, average CS values of samples ranged from 64.21 $N/mm^2$ (200°C) to 71.27 $N/mm^2$ (160°C) in solid wood groups. At relatively low temperatures, some increases in CS values (up to 3.72% (at 160°C) were obtained. However, intensive heat treatment caused some

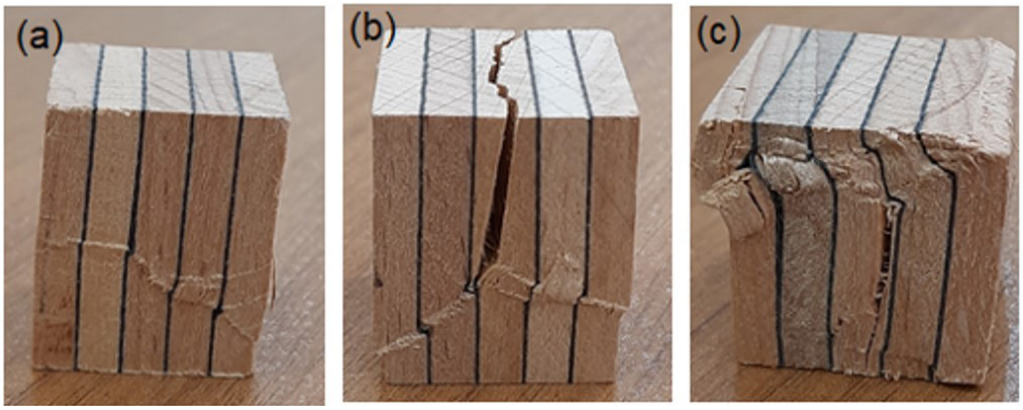


**Figure 5.** Failure modes in compression parallel to the grain of specimens reinforced LVL. (a) Shearing failure; (b) Splitting and shearing failure; (c) crushing and splitting.

**Table 2.** Results of the Duncan tests of the Specimens.

| Group of Samples | Heat Treatment (°C) | CS (N/mm²) (Mean value) | SD (Standard deviation) | HG (Homogeneity groups) | Changes (%) |
|---|---|---|---|---|---|
| Solid Wood (Beech) | Control | 68.62 | 3.83 | P | - |
| | 140 | 69.11 | 4.31 | OP | 0.71 |
| | 160 | 71.27 | 3.37 | M | 3.72 |
| | 180 | 67.48 | 3.02 | Q | -1.69 |
| | 200 | 64.21 | 3.10 | S | -6.83 |
| PVAc-LVL | Unheated | 69.53 | 3.58 | O | 1.31 |
| | 140 | 72.47 | 3.86 | L | 5.31 |
| | 160 | 74.61 | 3.48 | K | 8.03 |
| | 180 | 72.71 | 4.11 | L | 5.63 |
| | 200 | 64.29 | 3.76 | S | -6.80 |
| PF-LVL | Unheated | 72.29 | 4.05 | L | 5.08 |
| | 140 | 74.62 | 3.85 | K | 8.04 |
| | 160 | 77.58 | 3.22 | I | 11.55 |
| | 180 | 77.07 | 3.69 | IJ | 10.96 |
| | 200 | 72.98 | 4.04 | L | 5.97 |
| PU-LVL | Unheated | 70.49 | 4.41 | MN | 2.65 |
| | 140 | 72.91 | 3.46 | L | 5.88 |
| | 160 | 75.37 | 3.90 | K | 8.96 |
| | 180 | 69.72 | 4.09 | NO | 1.58 |
| | 200 | 65.49 | 4.31 | R | -4.78 |
| PVAc-RLVL | Unheated | 76.37 | 3.56 | J | 10.15 |
| | 140 | 80.22 | 4.57 | G | 14.46 |
| | 160 | 83.11 | 4.21 | E | 17.43 |
| | 180 | 78.89 | 3.98 | H | 13.02 |
| | 200 | 69.33 | 4.35 | OP | 1.02 |
| PF-RLVL | Unheated | 82.19 | 4.29 | F | 16.51 |
| | 140 | 86.11 | 3.44 | C | 20.31 |
| | 160 | 90.61 | 3.59 | A | 24.27 |
| | 180 | 88.47 | 3.47 | B | 22.44 |
| | 200 | 83.34 | 3.33 | DE | 17.66 |
| PU-RLVL | Unheated | 76.45 | 3.41 | J | 10.24 |
| | 140 | 80.34 | 3.76 | G | 14.59 |
| | 160 | 83.96 | 3.46 | D | 18.27 |
| | 180 | 76.57 | 3.14 | J | 10.38 |
| | 200 | 74.65 | 3.37 | K | 8.08 |

decreases (6.83% at 200°C). In PVAc-LVL group, average CS of samples were ranged from 69.53 N/mm² (unheated) to 74.61 N/mm² (at 160°C). In this group, CS increased from 1.31% (unheated) to 8.03% (at 160°C) but decreased by 6.80% (at 200°C) according to control samples. Considering the PF-LVL group, average CS of samples ranged from 72.98 N/mm² (at 200 °C) to 77.58 N/mm² (at 160°C). The CS increased from 5.08% (unheated) to 11.55% (at 160°C). However, as the heat treatment temperature increased, CS value presented a declining trend.

Considering the reinforced samples, an increase of CS was observed for all LVL made with the addition of carbon fibres compared to the control samples. All the CS values in PVAc-RLVL group increased. The increases were 10.15% (unheated), 14.46% (at 140°C), 17.43% (at 160°C), 13.02% (at 180°C), and 1.02% (at 200°C) compared to the control samples. However, as the heat treatment conditions got harsher, CS value displayed a declining trend, especially at 200°C. Regarding the PF-RLVL group the highest CS value was determined in samples that were heat treated at 160 °C. Average CS values of this samples significantly increased according to control samples. In addition, the CS values of the reinforced samples were higher than the massive and LVL samples that were heat treated at the same temperature. The CS value increased by 16.51% in unheated samples, by 20.31 at 140°C, by 24.27% at 160°C, by 22.44% at 180°C, and by 17.66% at 200°C. In PU-RLVL group, CS value of all reinforced samples were higher than that of the control samples. Regarding the increase, rates were 10.24% for unheated samples, 14.59% at 140°C, 18.27% at 160°C, 10.38% at 180°C, and 8.08% at 200°C.

The obtained results showed that the three lower temperatures have a positive effect on CS, while the heat treatment at a temperature of 200 °C reduced it. In many studies in the literature, it has been stated that the heat treatment temperatures applied approximately up to 170 °C are critical point for wood material[35,56,57]. Hidayat et al. [58] reported CS values of the wood material decreased

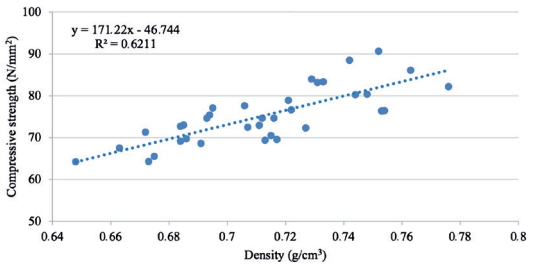


**Figure 6.** Linear regression and the coefficient of determination ($R^2$) of wood density and CS.

depending on the heat treatment temperature, also there was no significant change in the range of 160°C to 180°C, however, significant strength losses were determined at temperatures above 200°C and 220°C. The increase in CS values after heat treatment at relatively low temperatures can be explained by the decrease in moisture content due to the increase in cellulose crystallinity[18], while the significant losses in mechanical strength at high temperatures can be explained by the chemical change and the degradation of chemical components of the wood[40,58,59]. Therefore, using carbon fibre fabric and PF could improve the CS of LVL. The maximum increase was determined in reinforced samples that were laminated with PF similar results found by Perçin and Altunok[2]. The anatomical structure and density of the wood material significantly affect its mechanical properties, including compressive strength parallel to the grains[52,60-64].

As can be seen in Figure 6, wood density had a significant linear relationship with CS ($R^2$= 0.6211 and P= 0.0082). It was found to be a significant correlation among density and compression strength parallel to the grain. Wood density is a commonly used wood quality indicator that is related to other wood mechanical strength[65,66].

## 4. Conclusions

The results of an experimental test of the reinforcement by carbon fibres on compressive strength parallel to the grain of LVL bonded with phenol-formaldehyde (PF), polyvinyl acetate (PVAc) and polyurethane adhesives (PU) using thermally modificated beech (*Fagus orientalis*) veneers. The results showed that thermally modification reduced density of beech wood. Moreover, higher temperatures gave lower density after heat treatment. Carbon fibre reinforcement placed within the layers increased density in all reinforced specimens. The results demonstrated that the density values of samples were heavily dependent on carbon fibre, properties of the adhesives used and press conditions. The results also confirmed compressive strength parallel to the grain increased up to 160 °C after then it yielded a declining trend. Different failure behavior (abrupt fracture at medium and higher temperature) of heat-treated wood was observed during the CS tests. While plastic deformation forms were formed in the samples that were not heat-treated, sudden rupture types were commonly determined due to the increase in temperature. CS values increased at low temperature, while it decreased with increasing treatment temperature. Therefore, increase of CS was observed for all specimens made with the addition of carbon fibre fabrics bonded with different adhesive compared to the unreinforced and solid wood and CS of all the thermally modificated specimens were significantly improved. It was evident from experimental results, the PF adhesive provided better results compared to others. In future studies, carbon fiber material is an effective material against combustion, topics related to combustion or combustion after the pyrolysis process of wood.

## 5. Author's Contribution

- **Conceptualization** – Onur Ülker; Osman Perçin.
- **Data curation** – Osman Perçin; Onur Ülker.
- **Formal analysis** – Onur Ülker.
- **Funding acquisition –** Osman Perçin.
- **Investigation** – Onur Ülker; Osman Perçin.
- **Methodology** – Onur Ülker; Osman Perçin.
- **Project administration** – Onur Ülker
- **Resources** – Osman Perçin; Onur Ülker.
- **Software** – Osman Perçin; Onur Ülker.
- **Supervision** – Osman Perçin
- **Validation** – Onur Ülker
- **Visualization** – Onur Ülker
- **Writing – original draft** – Onur Ülker; Osman Perçin.
- **Writing – review & editing** – Onur Ülker; Osman Perçin.

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