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Araştırma Makalesi

Effects of heat treatment on elastic constants of Cedar (*Cedrus libani*) wood

Isıl işlemin Sedir (*Cedrus libani*) odununun elastik sabitleri üzerine etkileri

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Abstract

The aim of this study was to evaluate the effects of heat treatment on the elastic constants of Cedar (*Cedrus libani*) wood. Heat under atmospheric pressure at three different temperatures (150, 180 and 210 °C) and three different time levels (2, 5 and 8 hours) was applied to Cedar wood specimens and its Modulus of elasticity (E_L, E_R, E_T) shear modulus (G_{LR}, G_{LT}, G_{RT}) and Poisson's ratios (ν_{LR}, ν_{LT}, ν_{RL}, ν_{RT}, ν_{TL}, ν_{TR}) were evaluated by compression tests conducted on 20 x 20 x 60 mm samples using bi-axial extensometer. It was observed that the modulus of elasticity, shear modulus, and compression strength of the tested specimens were significantly affected by the temperature and time parameters of the heat treatment. Treatment of heat for low temperatures and short periods yielded some increase in modulus of elasticity but an increase in time and temperature resulted in a significant decrease. Heat treatment has a devastating influence on the shear modulus. Poisson's ratios were less sensitive to the heat treatment. Heat treatment significantly alters the modulus of elasticity, shear modulus and compression strength of Cedar wood.

Keywords: Cedar wood, elastic constants, heat treatment.

Özet

Bu çalışmanın amacı ısıl işlemin Sedir (*Cedrus libani*) odununun elastik sabitleri üzerindeki etkilerinin araştırılmasıdır. Sedir odunu örnekleri atmosferik basınç altında üç farklı sıcaklıkta (150, 180 ve 210 °C) ve üç farklı zaman seviyesinde (2, 5 ve 8 saat) ısıya maruz bırakılmıştır. Elastikiyet modülü (E_L, E_R, E_T), kesme modülü (G_{LR}, G_{LT}, G_{RT}) ve Poisson oranları (ν_{LR}, ν_{LT}, ν_{RL}, ν_{RT}, ν_{TL}, ν_{TR}) 20 x 20 x 60 mm numuneler üzerinde gerçekleştirilen basma testlerinde çift eksenli ekstensometre kullanılarak belirlenmiştir. Test edilen numunelerin elastikiyet modülü, kesme modülü ve basma dirençleri ısıl işlemde sıcaklık ve zaman parametrelerinin önemli bir etkisi olduğu gözlemlenmiştir. Düşük sıcaklıklar ve kısa süreler için ısıl işlem, elastikiyet modülünde bir miktar artış sağlamış, ancak süre ve sıcaklığın artması, önemli ölçüde azalmaya neden olmuştur. Isıl işlem, kesme modülü üzerinde yıkıcı etkiye sahiptir. Poisson oranlarının ısıl işleme daha az duyarlı görülmüştür. Isıl işlem sedir odununun elastikiyet modülü, kayma modülü ve basma direncini önemli ölçüde değiştirmektedir.

Anahtar kelimeler: Sedir odunu, elastik sabitler, ısıl işlem.

1. Introduction

Wood modification using a heat-treatment process offers benefits regarding durability and dimensional stability but alters the mechanical properties of wood. Nowadays, utilization of heat-treated wood is getting more interest in architectural design (Kuzman, et al., 2015). The need for sustainable building materials, decrease in durable timber, deforestation of subtropical forests-and restrictive regulations are increasing the demand for heat-treated wood (Boonstra, 2008). In the process, temperatures up to 160–250 °C are applied to wood, depending on the species used and the desired material properties (Kocaefe et al., 2008). Thermal modification results in some loss in mechanical properties, which restricts the use in structural applications (Fajdiga et al., 2016), due to the damage that occurs in the cell-wall components (Fengel and Wegener, 2003; Windeisen et al., 2007).

The increase in demand for heat-treated wood has led to the development of different processes in different countries. This increase can also be seen in the number of scientific studies conducted. Esteves and Pereira (2009) summarized the selected properties for heat-treated wood. In general, this process mainly results in the darkening of color, low equilibrium moisture content, mass loss, dimensional stabilization, and low mechanical properties.

Elastic constants are significant in the design of wood members in structures. All elastic constants of heat-treated wood are scarce. The available information is limited to a few references. While mechanical properties in the L direction for some heat-treated wood species have been reported, the information on the perpendicular directions is unknown.

Nine independent elastic constants are necessary input parameters for numerical analysis, such as finite element models. All elastic constants of cedar wood have been studied by Güntekin (2023). Although heat-treated wood has been restricted in structural applications, elastic constants can be used to model non-structural applications such as outdoor furniture. In this study, elastic constants for heat-treated Cedar wood were evaluated using compression tests under constant moisture conditions. Compression strength in three orthotropic directions was also determined.

2. Materials and Method

Clear wood specimens were cut from Cedar logs, which are grown in a forest district in the southwestern Turkey. The diameter of the logs was approximately 50 cm. The logs were sawn into 25 mm thick radial or tangential planks. Specimens were exposed to heat applied in a temperature-controlled oven under atmospheric pressure at three different temperatures (150, 180 and 210 °C) and three different time levels (2, 5 and 8 hours). Commercial heat treatment processes are applied in oxygen-free atmosphere. The presence of oxygen will lead to oxidative reactions. As a result of oxidation, wood subjected to heat treatment tends to lighten with time. Before testing and after the heat treatment process, specimens were conditioned in climatic chambers at 65 % relative humidity (RH) at a temperature of 20±1 °C. To minimize the influence of the MC change, specimens were tested immediately after removal from the climatic chamber. MC of the wood was calculated by the oven-drying method. The apparent densities of the samples were determined using a stereo-metric method based on measurements of the sample volume and mass.

Elastic moduli (E_i) in three anisotropic directions (L, R, T), three shear modulus (G_{ij}), and six Poisson’s ratios (ν_{ij}) were determined using a bi-axial extensometer on 20 x 20 x 60 mm samples (Figure 1 and 2) subjected to compression. Strength values (C.S.) were also calculated. The speed of testing was 2 mm/min. The stress-strain diagrams were recorded and used to calculate the elastic constants. The E_i was the ratio of the stress (σ) to the strain (ε) measured in the linear elastic region (Equation 1).

$$E_i = \frac{\Delta\sigma_i}{\Delta\varepsilon_i} = \frac{\sigma_{i,2}-\sigma_{i,1}}{\varepsilon_{i,2}-\varepsilon_{i,1}} \quad i \in R, L, T \tag{1}$$

The νij, defined as in Equation 2:

$$\nu_{ij} = -\frac{\varepsilon_j}{\varepsilon_i}, \quad i, j \in R, L, T \text{ and } i \neq j \tag{2}$$

where, εi represents the active strain in the loading direction, and ε_j is the passive (lateral) strain.

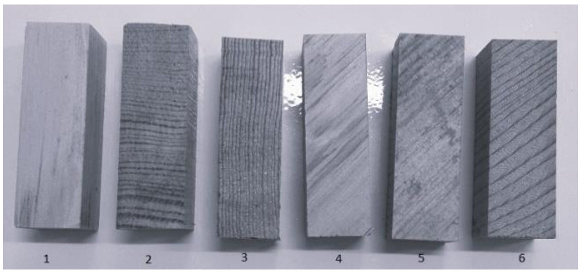

Figure 1. Samples and properties determined (1- E_L, ν_{LR}, ν_{LT}, L direction compression strength, 2:- E_R, ν_{RL}, ν_{RT}, R direction compression strength, 3- E_T, ν_{TL}, ν_{TR}, T direction compression strength, 4- G_{LR}, 5-G_{TL}, 6- G_{RT}).

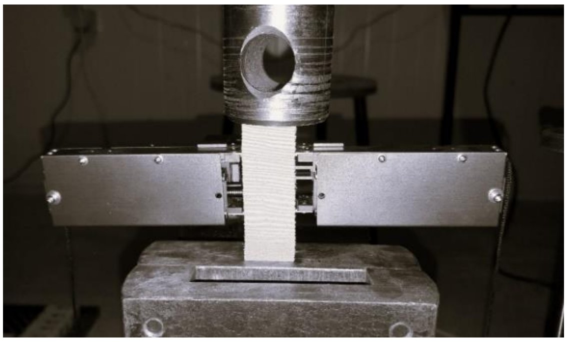

Figure 2. Compression test using bi-axial extensometer.

The maximum C.S. value was taken as 0.2% yield using Equation 3.

$$\sigma_{CS} = P_{max}/A \tag{3}$$

where, σ_{CS} is compression strength (in N/mm^2), P_{max} is the % 0.2 yield load (N), and A is the cross-sectional area (mm^2). The G_{ij} of the specimens with a 45° angle in the LR, LT and RT planes were determined using equations 4-6.

$$G_{LR} = \frac{\tau_{LR}}{\gamma_{LR}} = \frac{\sigma_V}{2\,(\varepsilon_H - \varepsilon_V)} \tag{4}$$

$$G_{LT} = \frac{\tau_{LT}}{\gamma_{LT}} = \frac{\sigma_V}{2\,(\varepsilon_H - \varepsilon_V)} \tag{5}$$

$$G_{RT} = \frac{\tau_{RT}}{\gamma_{RT}} = \frac{\sigma_V}{2\,(\varepsilon_H - \varepsilon_V)} \tag{6}$$

where, σ_V is the vertical stress, ε_H is the horizontal strain, and ε_V is the vertical strain. Aira et al. (2014) explain how to calculate shear modulus from angled specimens in compression tests. In order to interpret the effects of temperature and duration of exposure on the properties measured of the clear wood samples, the analysis of variance (ANOVA) procedure was applied using IBM SPSS statistical analysis software.

3. Results and Discussion

Calculated values for the Ei and C.S. of heat-treated Cedar wood as affected by heat treatment are presented in Tables 1-3. Average densities of the control samples tested in this study specimens ranged from 0.48 to 0.56 g/cm^3, which is identical to the densities of cedar wood presented in the literature (Demetci, 1986; As et al., 2001; Bal et al., 2012, 2013; Aydın, 2021; Efe, 2021). The bending modulus of elasticity (MOE) of untreated cedar wood reported in the literature varied from 7000 to 10000 N/mm^2 (Demetci, 1986; As et al. 2001; Bal et al., 2012, 2013; Aydın, 2021; Efe, 2021) for the higher densities Brunetti et al., (2001) reported that the MOE of Atlas cedar wood, which has similar density values, is slightly over 10000 N/mm^2. Mass loss or reduction in the densities is the most profound effect attained by the heat treatment, which has also been observed for cedar wood (Tables 1-3).

Values of the E_i of the tested samples were decreased by up to % 25 when the temperature was raised to 210 °C. The decrease is the greatest in the T direction. Test results show that 150 °C - treatments increase the E by up to % 15 while 180 and 210 °C - treatments decrease the E values by up to % 20 in the longitudinal direction. The effect is similar in the radial direction but more severe in the tangential direction.

Test results show that 150 and 180 °C - treatments increase the C.S. by up to 12%, while 210 °C - treatments decrease the compression strength by up to12% in the longitudinal direction. The effect of heat treatment on C.S. is entirely different in perpendicular directions. In radial directions, all treatments yielded some amount of decrease while in the tangential directions only 180 and 210 °C - treatments decreased the compression strength.

Table 1. E and C.S. values calculated in the L direction.

T	D	d_{12} (g/cm^3)	MC (%)	E (N/mm^2)	C.S. (N/mm^2)
150	0	0.49	12.6	7410 (12)	43.4 (6.4)
	2	0.48	10.1	8112 (13)	46.2 (8.0)
	5	0.48	9.1	8286 (9)	48.5 (9.2)
	8	0.48	9.0	7895 (10)	49.6 (4.5)
180	0	0.49	12.2	7800 (10)	42.4 (7.2)
	2	0.46	6.9	7480 (7)	45.3 (5.8)
	5	0.46	6.3	7390 (10)	46.0 (4.3)
	8	0.44	6.1	7321 (8)	44.2 (5.0)
210	0	0.52	12.1	7912 (9)	45.1 (6.9)
	2	0.50	5.9	7205 (8)	43.8 (5.2)
	5	0.48	4.5	6711 (10)	42.0 (6.2)
	8	0.46	4.5	6302 (11)	41.2 (5.7)

Table 2. E and C.S. values calculated in the R direction

T	D	d_{12} (g/cm^3)	MC (%)	E (N/mm^2)	C.S. (N/mm^2)
150	0	0.49	12.4	902 (8.2)	8.2 (7.8)
	2	0.48	10.4	942 (9.9)	8.0 (5.3)
	5	0.48	9.5	924 (9.4)	7.5 (6.8)
	8	0.46	9.1	916 (9.8)	7.2 (8.8)
180	0	0.51	12.2	912 (10.7)	7.9 (9.7)
	2	0.47	7.1	862 (12.8)	7.4 (5.5)
	5	0.46	6.5	842 (11.6)	7.2 (9.3)
	8	0.45	6.3	829 (11.6)	6.9 (6.1)
210	0	0.56	11.9	892 (12.2)	9.1 (6.6)
	2	0.53	7.1	825 (10.3)	8.5 (7.9)
	5	0.50	4.8	742 (12.4)	7.6 (8.6)
	8	0.49	4.5	720 (12.0)	6.9 (6.8)

* Values in parentheses are coefficient of variations

Table 3. E and C.S. values calculated in the T direction

T	D	d_{12} (g/cm^3)	MC (%)	E (N/mm^2)	C.S. (N/mm^2)
150	0	0.50	12.22	690 (10.5)	8.0 (8.5)
	2	0.49	10.11	710 (10.9)	8.4 (8.6)
	5	0.48	9.10	760 (9.6)	8.3 (10.6)
	8	0.48	9.00	788 (10.1)	8.4 (7.1)
180	0	0.48	11.97	700 (11.4)	8.6 (4.6)
	2	0.45	6.98	658 (10.5)	8.3 (5.1)
	5	0.44	6.76	639 (10.7)	8.1 (7.7)
	8	0.43	6.29	612 (9.8)	8.0 (6.4)
210	0	0.51	12.66	690 (9.7)	7.9 (4.4)
	2	0.48	7.14	610 (8.0)	7.6 (8.0)
	5	0.47	5.41	566 (10.9)	7.0 (6.4)
	8	0.46	5.29	530 (11.7)	6.8 (3.6)

* Values in parentheses are coefficient of variations

In the literature, the effect of heat treatment on compressive strength seems contradictory. While some studies (Ünsal and Ayrılmış, 2005; Korkut et al., 2008a; Korkut et al., 2008b) reported a negative effect of heat treatment on C.S., the others (Boonstra and Blomberg, 2007; Altınok et al., 2010) revealed a positive effect with heat treatment.

A slight increase in the C.S. in the L direction was also reported for poplar, beech, and ash woods after the heat treatment (Windeisen et al., 2008; Taghiyari et al., 2012). Heat treatment has a more profound effect on the strength of the wood than elasticity (Esteves and Pereira, 2009). According to Esteves and Pereira (2009) exposure to low temperatures yields an increase in the bending MOE values while exposure to high temperatures results a decrease. Studies conducted by Kubojima et al. (1998) and Altınok et al., (2010) confirm this idea. A study by Yang et al. (2016) showed that heat treatment has no significant influence on C.S. in the L direction of Japanese cedar.

Xie et al. 2020 reported a significant reduction (up to 38-33%) in bending strength, C.S., and MOE of Toona wood treated at 220 °C for 6 hours. Akyürek et al. (2020) also reported a significant decrease in the C.S. of black pine wood after heat treatment at 250 °C for 2 hours. Contrary to those reported above, some researchers reported particular increases in the C.S. after heat treatment (Kol, 2010, Perçin et al., 2016). ThermoWood Handbook (2003) also reports a 30% increase for in C.S. of spruce wood treated at 195 °C for 3 hours.

The radial mechanical properties of wood are mainly controlled by the hemicellulose in the S_1 and S_3 layers, while S_2 layer governs the mechanical properties in the L directions (Bergander and Salmén, 2002). The strength properties can be reduced due to thermal degradation and mass loss after heat treatment. The decrease in strength can be explained by the depolymerization reactions of wood polymers (Kotilainen, 2000) or the decomposition of the cell wall components (Yıldız et al., 2006). According to Hillis (1984), the primary source of strength reduction is the degradation of hemicelluloses, which are less heat-resistant than cellulose and lignin. The increase in strength during heat treatment is usually attributed to the increase in crystallinity of cellulose and cross-linking reactions (ThermoWood Handbook, 2003). FTIR analysis conducted on the heat-treated cedar wood samples by Tufan (2016) revealed that the highest increase in the crystallinity index occurred at 180 °C, and the lowest increase occurred at 120 °C while the index started to decrease after reaching 210 °C.

The average values of G_{ij} for heat-treated Cedar wood are presented in Tables 4-6. The shear behavior of heat-treated wood is not well understood. In general, the shear behavior of wood is controlled by density and MC, temperature, and fiber direction (Brandner et al., 2007). While the decrease in densities of the heat-treated wood may negatively contribute to G_{ij} values, low MC values may have a positive effect. In general, most of the treatments decreased the values of G_{ij}, but the decrease is severe in the RT plane. Test results show that – heat treatments with temperatures of 150 and 180 °C insignificantly increased the G_{LR} in the initial stages and decreased afterward. The final G_{RT} values of treated samples were significantly reduced (up to 64%) comparing to the G_{RT} of the control samples. A study by Kubojima et al., (1998) indicated that the shear modulus in longitudinal and radial directions increased for low temperatures and short periods of exposure and decreased for high temperatures and longer exposures.

Esteves and Pereira (2009) summarized that heat treatment may cause micro-cracks and other anatomical changes, such as an increase in porosity. Extreme reduction of G_{ij} values for cedar wood in the RT plane can be due to such anatomical changes.

Table 4. G_{RT} values of heat-treated Cedar wood.

T ° C	D (hour)	d_{12} (g/cm^3)	MC (%)	G_{RT} (N/mm^2)
150	0	0.47	12.6	354 (18)
	2	0.45	10.1	184 (24)
	5	0.45	9.1	129 (14)
	8	0.42	9.1	127 (22)
180	0	0.46	12.2	244 (14)
	2	0.44	6.9	210 (15)
	5	0.43	6.3	155 (29)
	8	0.42	6.1	137 (15)
210	0	0.49	12.1	328 (18)
	2	0.47	5.9	174 (17)
	5	0.45	4.5	192 (6)
	8	0.42	4.5	189 (15)

* Values in parentheses are coefficient of variations

Table 5. G_{LT} values of heat-treated Cedar wood.

T ° C	D (hour)	d_{12} (g/cm^3)	MC (%)	G_{LT} (N/mm^2)
150	0	0.47	12.6	790 (5)
	2	0.45	10.1	782 (5)
	5	0.44	9.1	780 (4)
	8	0.43	9.0	741 (8)
180	0	0.48	12.1	808 (16)
	2	0.46	6.8	669 (6)
	5	0.43	6.3	616 (8)
	8	0.42	6.1	547 (4)
210	0	0.49	12.1	1133 (14)
	2	0.47	6.0	903 (10)
	5	0.45	4.5	769 (27)
	8	0.42	4.4	788 (3)

* Values in parentheses are coefficient of variations

Table 6. G_{LR} values of heat-treated Cedar wood.

T ° C	D (hour)	d_{12} (g/cm^3)	MC (%)	G_{LR} (N/mm^2)
150	0	0.48	12.5	868 (2)
	2	0.45	10.0	899 (6)
	5	0.44	9.1	894 (6)
	8	0.42	9.0	852 (6)
180	0	0.49	12.0	1084 (3)
	2	0.46	6.6	1147 (11)
	5	0.43	6.4	787 (3)
	8	0.42	6.1	742 (5)
210	0	0.49	12.1	1282 (4)
	2	0.47	5.9	899 (9)
	5	0.45	4.4	906 (16)
	8	0.41	4.3	923 (5)

* Values in parentheses are coefficient of variations

Poisson's ratios are less investigated elastic constants, because their determination requires delicate instruments. The value of Poisson's ratios is dependent on specific gravity and MC (Ross, 2010). The effects of heat treatment on Poisson's ratios are presented in Table 5. There is no information concerning the effects of heat treatment on Poisson's ratios for wood materials. Although there are fluctuations in the Poisson's values, statistical analysis resulted in insignificant effects of heat treatment on the Poisson's ratios.

The Poisson's ratio is 0.3 accepted as isotropic material property for numerical analysis of wood. It was found that the Poisson's ratio varies from 0.05 in the RL plane to 0.499 in the LT plane for control groups. In general, calculated the Poisson's ratios in the RL and TR planes are identical and higher in the LR, LT, RT and TL planes than those reported for softwood species by Ross (2010). A high coefficient of variations for Poisson's ratios was obtained which is also observed in the investigations of Hering et al. (2012); Ozyhar et al. (2013); Jeong et al. (2010); Mizutani and Ando (2015).

4. Conclusions

The results of the study are generally compatible with the literature. Wood is generally accepted as a material with orthotropic symmetry, which comprises nine independent elastic constants. Heat treatment significantly alters physical, chemical and mechanical properties of wood. Lower temperatures and duration of exposures resulted in some improvements in elastic constants probably due to lower EMC. Longer and higher treatment conditions significantly decreased E_i, G_{ij} and C.S. values measured. Poisson's ratios seem to be not sensitive to the heat treatment applied. The fact that the wood is cylindrical orthotropic and variation in the formation and arrangement of wood cells may have caused a fluctuation in Poisson's ratios.

Table 7. Poisson's ratios affected by heat treatment.

(°C)	Hour	υ_{LR}	υ_{LT}	υ_{RL}	υ_{RT}	υ_{TL}	υ_{TR}
150	Control	0.468 (18)	0.491 (13)	0.049 (16)	0.499 (15)	0.052 (13)	0.396 (14)
	2	0.477 (15)	0.518 (16)	0.051 (17)	0.510 (16)	0.051 (11)	0.388 (13)
	5	0.450 (13)	0.517 (11)	0.052 (12)	0.512 (14)	0.061 (15)	0.397 (13)
	8	0.416 (13)	0.511 (13)	0.059 (11)	0.522 (14)	0.065 (14)	0.375 (15)
180	Control	0.451 (14)	0.472 (16)	0.040 (15)	0.594 (14)	0.047 (12)	0.461 (12)
	2	0.410 (17)	0.482 (15)	0.046 (14)	0.633 (13)	0.059 (15)	0.482 (15)
	5	0.492 (15)	0.495 (15)	0.048 (11)	0.646 (15)	0.052 (14)	0.474 (12)
	8	0.482 (14)	0.514 (13)	0.053 (13)	0.642 (16)	0.053 (16)	0.495 (15)
210	Control	0.463 (12)	0.475 (15)	0.058 (14.29)	0.529 (15)	0.061 (15)	0.571 (12)
	2	0.485 (15)	0.492 (14)	0.056 (14)	0.522 (15)	0.059 (13)	0.573 (14)
	5	0.494 (15)	0.508 (10)	0.059 (10)	0.585 (12)	0.063 (14)	0.571 (9)
	8	0.517 (14)	0.511 (12)	0.061 (11)	0.588 (17)	0.069 (12)	0.597 (14)

Yazar katkıları

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Etik kurul izni

Bu çalışmada etik kurul izni gerekmemektedir

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