İleri Teknoloji Bilimleri Dergisi
Journal of Advanced Technology Sciences
ISSN:2147-345

EFFECT OF HEAT TREATMENT ON THE MECHANICAL PROPERTIES AND DIMENSIONAL STABILITY OF BEECH WOOD

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Abstract-Thermal modification at different temperatures especially at high temperatures is an effective method to change chemical, physical, and mechanical properties of wood. In this study, some mechanical and physical properties of heat treated beech (*Fagus orientalis*) wood at temperatures 170, 180, 190, and 212ºC for 2 h with ThermoWood method were investigated. The results were compared with oven-dried reference samples. Consequently, depending on the increase of heat treatment temperature, the bending strength was decreasing, the compression strength parallel to the grain and modulus of elasticity increased. Also, when the treatment temperature increased, equilibrium moisture content decreased. It was seen that a significant increase of dimensional stability and besides the color of samples was darken uniformly.

Key Words- Mechanical properties, Heat treatment, Color, Dimensional stability, Thermowood.

ISIL İŞLEMİN KAYIN ODUNUN MEKANİK ÖZELLİKLERİ VE BOYUTSAL KARARLILIĞI ÜZERİNE ETKİSİ

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Özet: Farklı sıcaklıklarda özellikle yüksek sıcaklıklardaki termal modifikasyon odunun kimyasal, fiziksel ve mekanik özelliklerini değiştirmede etkili bir metottur. Bu çalışmada, ThermoWood metoduyla 170, 180, 190, ve 212 oC sıcaklıkta 2 saat süre ile ısıl işlem görmüş kayın odununun bazı mekanik ve fiziksel özellikleri araştırılmıştır. Sonuçlar tam kuru referans örnekler ile karşılaştırılmıştır. Sonuç olarak, ısıl işlem sıcaklığının artmasına bağlı olarak, eğilme direnci azalırken, liflere paralel basınç direnci ve elastikiyet modülü artmıştır. Ayrıca, işlem sıcaklığı yükseldikçe, denge rutubet miktarı azalmıştır. Boyutsal stabilizasyonda önemli ölçüde artış görülmüş ve bunun yanında odun örneklerinin rengi yeknesak bir şekilde koyulaşmıştır.

Anahtar Kelimeler- Mekanik özellikler, Isıl işlem, Renk, Boyutsak kararlılık, Thermowood.

1. GİRİŞ (INTRODUCTION)

Heat treatment is the well-known method to improved wood properties against to moisture, decay, climate conditions etc. Furthermore, it improves dimensional stability and durability of wood without the need of any toxic chemicals.

There are four different heat treatment methods of wood that are common: The Finnish process (ThermoWood) uses steam, German method (OHT-Oil Heat Treatment) heated oil, the Dutch method (Plato Wood) uses a combination of steam and warm air and the French processes (Rectification and Bois Perdure) an inert gas (Esteves et al., 2009; Rapp, 2001). The ThermoWood process which is known as the most successful method in Europe (Boonstra, 2008) was selected in this study.

Because of its wide application field such as exterior cladding, window and door joinery, paneling, garden furniture, sauna furniture, flooring and decking etc. mechanical properties and dimensional stability of heat-treated wood is significant (Yıldız *et* al., 2006; Özçifçi *et* al., 2009; Viitaniemi, 2000). In the application area where the load-bearing capacity is needed and the humid conditions like saunas, bathrooms and garden furniture the mechanical properties such as bending strength (MOR) and modulus of elasticity (MOE), compression strength parallel to grain and dimensional stability of wood are important.

According to several studies, while heat treatment develops dimensional stability of wood by reducing hygroscopicity (Yıldız *et* al., 2006; Viitaniemi, 1997; Santos, 2000) it causes negative effects like reduced mechanical properties (Cao *et* al., 2012; Yıldız et al., 2006; Esteves *et* al., 2007; Shi *et* al., 2007). Mechanical properties and dimensional stability are affected by treatment process type, the maximum treatment temperature and holding time at the treatment temperature and of course the chemical composition of wood that used (Shi *et al*., 2007; Windeisen *et al*., 2007).

Beech (*Fagus orientalis*) is the main wood species naturally grown and commonly used in the forest products industry in Turkey. Therefore, it is the potential wood species for industrial-scale heat treatment. The main objective of this study is to provide some information about the mechanical and physical properties of heat-treated beech wood using the ThermoWood process at various temperatures.

2. YÖNTEM (METHOD)

2.1. Wood species

The studied hardwood species is beech wood (*Fagus orientalis*). This species is known to have a low dimensional stability. Heat treatment is thus a necessary means to give it an added value. The sample trees used for the present study were obtained from the Bolu Forestry Departments.

2.2. Heat treatment

The thermal treatment has been performed with the ThermoWood® technology (Finnish Thermowood Association, 2003) by the Turkish company Nova Wood. To perform wood heat treatment, the oven temperature was held at 170, 180, 190 and 212°C for 2 hours.
Determination of the degree of thermal modification:

The weight loss that occurred by heat treatment was determined. As a beginning, the planks were conditioned to a constant weight then weighed before and after the heat treatment.

Weight loss (%), WL was calculated according to equation below;

$$WL = \frac{Wut - Wt}{Wut} * 100 \quad (1)$$

where, Wu is the weight of the sample before the heat treatment (g); Wt is the dry weight of the sample after the heat treatment (g).

Dry weight (g), Wdry, was calculated according to the equation below;

$$Wdry = 100 * \frac{Wu}{u + 100} \quad (2)$$

where, Wu is the weight of the sample at moisture content u (g); u is the moisture content of the sample (%).

The tests were carried out according to Turkish Standards (TSE) and 20 replicates were used in each test for treated and untreated beech. The properties were determined based on the specimens with dimension of 2x2x3 cm for equilibrium moisture content (TS 2471), 3x3x1,5 cm for anti-shrinkage efficiency (ASE_1) and anti-swelling efficiency (ASE_2) (radial, tangential and volumetric according to TS 4086), 2x2x3 cm for compression strength parallel to grain (TS 2595), 2x2x30 cm for bending strength (TS 2474), 2x2x30 cm for modulus of elasticity in bending (TS 2478). The differences in properties of heat treated beech wood was provided by calculating the property difference between heat treated and untreated wood samples of the same species as a percentage of the untreated wood property according to the equation below:

$$D(\%) = \frac{Mut - Mt}{Mut} * 100 \quad (3)$$

where, D (%) is difference of property (MOE, MOR, CS, Anti-Swelling and Anti-Shrinkage); M_{ut} is the mean value of untreated samples; and M_t is the mean value of the heat-treated samples.

3. BULGULAR VE TARTIŞMA (FINDINGS AND DISCUSSION)

The results of weight losses, equilibrium moisture content, shrinkage and swelling properties of the samples used in the tests are presented in Table I. Heat treatment improved dimensional stability, equilibrium moisture content, compression strength parallel to grain of wood (Table 1) but reduces bending strength (shown at Table 2).

3.1. Ağırlık kaybı (Weight loss)

The results showed that after the heat treatment the weight losses on the wood materials increased and the higher heat treatment temperature caused greater weight losses in the samples. Similar results have been indicated by several authors (Özçifçi et al., 2007; Rusche, 1973; Seborg et al., 1953; Stamm, 1956), it is obvious that when the treatment temperature increased, consequently the weight losses also increased. It is stated that in Table I the minimum weight losses (1,2%) in beech wood were in treated samples at 170 ºC, maximum weight losses (7,3%) were in treated samples at 212 ºC treatment temperature. In a similar result, Feist and Sell (1987) determined that the weight loss of beech wood was between 10-15% at temperature 180-200 °C.

Fengel (1966) found that the spruce wood has 0,8% weight loss at 170 °C and at temperature 200 °C this rate became 15,5%. The degradation of the polysaccharides after heat treatment results in weight loss and the density is reduced and which are greater at the higher treatment temperature (Vukas et al., 2010).

Table 1. Changes of some physical properties

Heat Treatment Temperature (°C)	Weight Loss after heat-treatment (%)	Equilibrium moisture content (%)	Volumetric swelling (%)	Volumetric shrinkage (%)	Tangential Swelling (%)	Radial Swelling (%)	Tangential Shrinkage (%)	Radial Shrinkage (%)
Cont	0	12,4 ± 0,29	20,89 ± 1,27	18,19 ±1,13	15,88 ± 1,25	5,00 ± 0,25	13,02 ± 1,02	5,16 ± 0,29
170	1,2 ± 0,14	9,8 ± 0,28	17,90 ± 0,31	16,63 ± 0,41	13,45 ± 0,12	4,46 ± 0,25	11,97 ± 0,30	4,67 ± 0,18
180	2,6 ± 0,13	8,5 ± 0,63	14,61 ± 0,45	14,13 ± 0,61	10,93 ± 0,46	3,68 ± 0,22	10,70 ± 0,57	3,42 ± 0,15
190	3,3 ± 0,14	7,3 ± 0,38	11,78 ± 0,61	11,97 ± 0,89	8,77 ± 0,56	3,01 ± 0,22	8,85 ± 0,70	3,12 ± 0,27
200	3,89 ± 0,14	6,4 ± 0,30	10,18 ± 0,74	9,36 ± 0,55	7,31 ± 0,63	2,86 ± 0,22	6,53 ± 0,45	2,84 ± 0,20
212	7,3 ± 0,15	5,8 ± 0,32	9,55 ± 0,47	8,8 ± 0,31	6,87 ± 0,37	2,67 ± 0,22	6,12 ± 0,26	2,68 ± 0,14

3.2. Denge rutubet miktarı (Equilibrium moisture content-EMC)

After heat treatment, the cell wall receives less water because there is a reduction in free radicals with heat treatment (Vukas et al., 2010). In the treated samples equilibrium moisture content decreased comparing with the control samples.

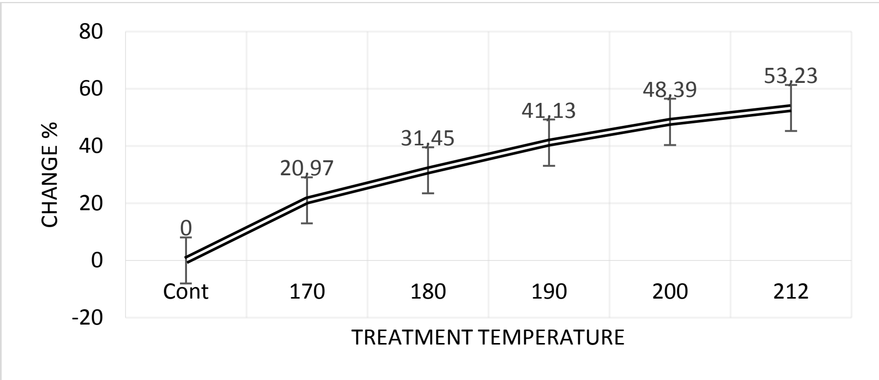

Figure 1. Increase rate of EMC

With increasing temperature, the equilibrium moisture content was reduced. When the minimum decrease of the equilibrium moisture content was 20,97 % at 170 °C, the maximum decrease of the equilibrium moisture content was 53,23% at 212 °C (Table I). The reasons of the decreasing equilibrium moisture content could be degradation of hemicelluloses and amorphous zone of cellulose (Vukas et al., 2010; Bhuiyan and Hirai, 2005; Tjeerdsma et al., 1998; Tjeerdsma and Militz, 2005; Esteves et al., 2007).

3.3. Boyutsal Kararlılık (Dimensional Stability)

ASE_1 of treated samples were increased compared with the control samples and with the increasing temperature, the ASE_1 of wood was also increased. When the minimum increase of the ASE_1 rate was 14,31 % at 170 °C, the maximum increase of the ASE_1 was 54,28 % at 212 °C (Figure 2).

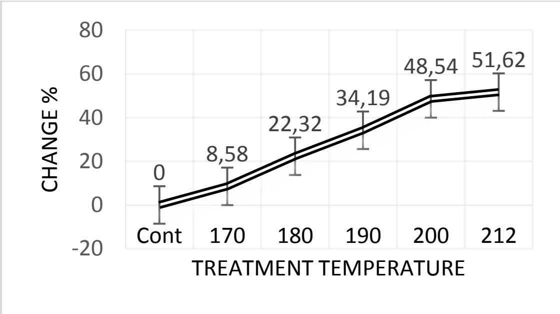

Figure 2. Increase rate of ASE_1

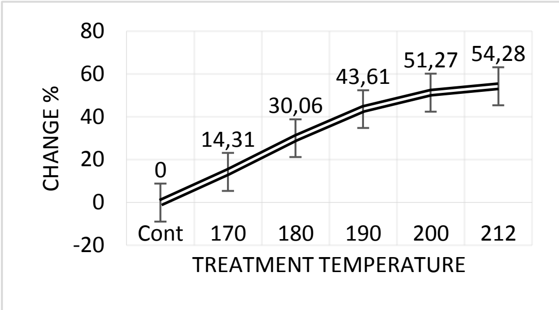

Figure 3. Increase rate of ASE_2

According to Stamm and Hansen (1937), when the samples were treated at 205 °C for 6 hours, the hygroscopicity of black gum wood decreased to half of its original value. ASE_2 of treated samples were increased compared with the control samples and with the increasing temperature, the ASE_2 of wood also increased. The minimum increase of ASE_2 was 8,58 % at 170 °C, while the maximum increase of the ASE_2 was 51,62% at 212 °C. Many studies show that the dimensional stability generally develops with the increasing treatment temperature and the treatment time. In addition, that the treatment technique also effects the dimensional stability (Stamm et al., 1946; Kaygın et al., 2009; Akyıldız et al., 2009; Esteves et al., 2007).

Degradation of wood during heat treatment starts at about 165 °C (Stamm and Hansen, 1937) and hemicelluloses are more affected by temperature than the other components (Fengel and Wegener, 1984). The degradation starts with hemicelluloses at first when wood is heated, and this degradation process is concluded with the production of methanol, acetic acid and various volatile heterocyclic compounds, such as furans, γ -valerolactone, etc. (Hill, 2006). It is believed that there is a relationship between volumetric shrinkage and weight loss of wood (Chang and Keith, 1978). Free hydroxyl groups of wood polysaccharides have a significant role on the absorption and desorption (Boonstra and Tjeerdsma, 2006). With the heat treatment, a reduction begins in free hydroxyls groups (Pizzi et al., 1994).

The improvement of the dimensional stability may be related to carbohydrates and especially depolymerization of hemicelluloses that results reducing of total amount of hydroxyl groups (Burmester, 1975; Kollman and Schneider, 1963). The hydroxyl groups are replaced by oxygen-acetyl groups after the heat treatment hence the dimensional stability is increased considerably (Cao et al., 2012).

3.4. Liflere paralel basınç direnci (Compression strength parallel to grain-CS)

The CS increased in heat treated Beech wood samples comparing to the control samples. When the minimum CS value of samples was 71,63 N/mm2 at 170°C, the maximum value was 77,71 N/mm2 at 212 °C (Table 2). According to test results CS was enhanced 4,02% at 170°C and this increase continued to the temperature of 212°C.

The similar test results are indicated in ThermoWood Handbook (2003) and, also Şahin Kol (2010) indicated that CS increased by 4,2% for treated at 212°C pine wood and 17% for treated at 190°C beech wood. Boonstra et al. (2007) exposed the Scots pine samples 2 stages (first step hydrolysis at 165 °C for 30 min and second step curing at 180°C for 6 h) heat treatment. The C was increased by 28% after treatment. Şahin Kol et al (2015) found that CS increased by 13,4% for treated at 212°C beech wood.

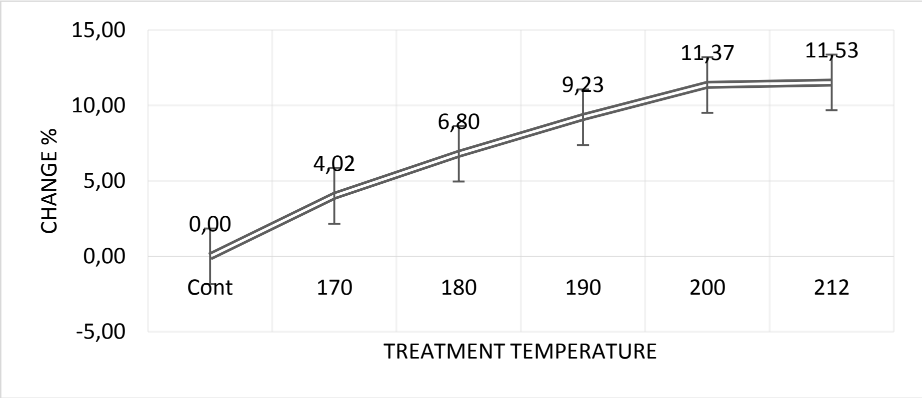

Figure 4. Increase rate of CS

Table 2. Changes on some mechanical properties

Heat Treatment Temperature (°C)	Compression resistance parallel to fibre (N/mm^2)	Bending Strength (N/mm^2)	Modulus of Elasticity (N/mm^2)
Control	68,75 ± 3,86	126,11 ± 5,24	12210,54 ± 773,55
170	71,63 ± 1,28	123,565 ± 18,22	12712,38 ± 1211,41
180	73,77 ± 3,18	120,89 ± 12,37	12730,1 ± 994,77
190	75,74 ± 2,75	117,83 ± 8,55	12658,68 ± 803,82
200	77,57 ± 3,64	113,84 ± 16,66	12403,61 ± 942,45
212	77,71 ± 4,95	109,09 ± 9,94	12349,04 ± 767,11

There might be a few reasons of increase of the compressive strength in longitudinal direction;

- decrease of amount of bound water in the heat-treated wood - Reducing hydrogen bonding between organic polymers (cell wall constitutes) depends on the increased amount of bound water and it is concluded with decreasing of the strength properties of wood because the strength is not only connected with covalent bounds but also hydrogen intramolecular bounds (Fengel and Wegener, 1984).
- increase of the crystalline cellulose due to degradation and/or crystallization of amorphous cellulose (Boonstra and Tjeerdsma, 2006),
- increase of cross linking of the lignin polymer network - improves the strength of the middle lamella which effects the strength properties of the cell wall (Boonstra and Tjeerdsma, 2006),
- degradation of the hemicelluloses matrix (Boonstra and Tjeerdsma, 2006),
- It might be also related to heat treatment method.

It can also find the reduced CS results (Schneider, 1973; Korkut, 2002; Unsal and Ayrılmış, 2005; Korkut et al., 2008; Yıldız et al., 2002).

3.5. Eğilme direnci (Bending strength-MOR)

Bending strength of treated samples was reduced when the comparing with control samples. The bending strength decreased with the increasing treatment temperature. When the minimum bending strength value of samples was 109,09 N/mm^2 at 212 °C, the maximum bending strength of samples was 123,565 N/mm^2 at 170 °C (Table 2).

According to test results MOR was reduced 2,02% at 170°C and this decrease continued with the 13,50 at the temperature of 212°C. The maximum reduction was 15% at temperature of 212°C (Figure 5). In many studies, it is clear that the heat treatment reduces the bending strength with the rates of 1-72% (Yıldız, 2002; Johansson and Moren, 2006; Esteves et al., 2007a; Esteves et al., 2007b; Shi et al., 2007; Korkut, 2008; Korkut et al., 2008).

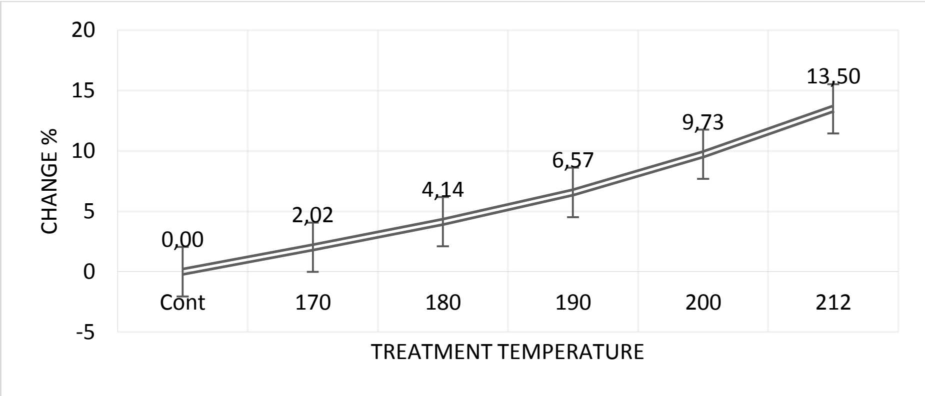

Figure 5. Decrease rate of MOR.

It is obvious that decrease in the bending strength is related to degradation of hemicelluloses. Because at lower treatment temperature, in cellulose and lignin neither depolymerization nor degradation are observed (Sweet and Winandy, 1999; Winandy and Lebow, 2001; Winandy and Morell, 1993).

3.6. Elastikiyet modülü (Modulus of elasticity-MOE)

MOE of treated samples increased when the comparing with control samples. With the increasing treatment temperature, the MOE increased, simultaneously. The minimum MOE value of samples was 12349,04 at 212 °C while the maximum MOE of samples was 12712,38 at 170 °C (Table 2). There was a significant increase between control samples and the heat-treated samples (Figure 6). But this increase has continued in descending order from temperature 170°C (3,95%) to 212°C (%1,12). Similar results are found when the literature is examined. Shi et al. (2007) indicated that there was an increase of 17% in MOE of wood.

Bekhta and Niemz (2003) showed that the change of modulus of elasticity value was insignificant. According to Hillis and Rozsa (1978), at the higher temperature and longer treatment time, because of wood consists of partially crystal micro fibrils and on a large-scale hemicelluloses and lignin, most of the amorphous polymeric components may convert their glassy structures to elastic.

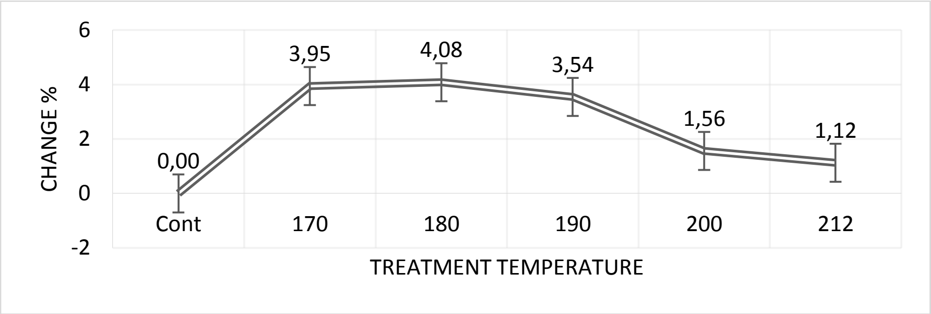

Figure 6. Change rate of MOE

At the conversion temperature from glassy structure to elastic, particular polymers have enough energy that reduces the mutual gravitational forces. Thus, the wood polymers can be converted to elastic or mostly plastic construction.

Noticeable increasing in the modulus of elasticity might be based on increasing of the relative cellulose content after heat treatment even though the hemicelluloses decomposed. Lower moisture content of treated wood than control ones also effects the modulus of elasticity (Boonstra, 2007).

4. SONUÇ (CONCULUSION)

The results of this study indicated that the compression resistance values of beech wood were increased with increasing temperatures which is the similar with literature. MOR values were reduced after heat treatment comparing with control samples. Reducing equilibrium moisture content of the treated wood is the most important property when the comparing to untreated wood and as a consequence of this reduction shrinkage and swelling of the wood is also reduced without using any water repellents.

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