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Effects of heat treatment on surface roughness and bonding strength of wood material

Osman Perçin*

Abstract

The purpose of this paper is to determine the effects of heat treatment on some properties of black pine (*Pinus nigra* A.) and larex (*Larix decidua*), woods. For this purpose, test samples were heat treated at 140, 160, 180 and 200°C for 2 and 5 hours. The air-dried density, equilibrium moisture content (EMC), surface roughness and bonding strengths of the test samples were analyzed. The average surface roughness parameter (*Ra*) was analyzed parallel to the grains. The results indicated significant differences depending on the wood species, heat treatment temperatures and treatment times. Based on the findings in this study, all parameters decreased depending on the heat treatment conditions. The density and EMC values of the control specimens were higher than the heat-treated samples. Also the surface roughness values obtained in black pine samples were higher than larex samples. On the other hand, bonding strength values obtained in larex samples were significantly higher than that of black pine samples. These parameters should be taken into account in the application areas of heat-treated wood material, the usage amount of which is constantly evolving in the woodworking industry.

Keywords: Bonding strength, Heat treatment, Surface roughness

Isıl işlemin ahşap malzemenin yüzey pürüzlülük ve yapışma direncine etkileri

Öz

Bu çalışmanın amacı, ısıl işlemin karaçam (*Pinus nigra* A.) ve lareks (*Larix decidua*), odunlarının bazı fiziksel ve mekanik özellikleri üzerine etkilerini belirlemektir. Bu amaçla, deney örneklerine 140, 160, 180 ve 200 °C'de 2 ve 5 saat ısıl işlem uygulanmıştır. Deney örneklerinin hava kurusu yoğunluk, denge rutubet miktarı (EMC), yüzey pürüzlülüğü ve yapışma dirençleri belirlenmiştir. Ortalama yüzey pürüzlülük parametresi (Ra) liflere paralel olarak analiz edilmiştir. Sonuçlar, ağaç türüne, ısıl işlem sıcaklığına ve işlem süresine bağlı olarak önemli farklılıklar göstermiştir. Bu çalışmadaki bulgulara göre tüm parametreler ısıl işlem sıcaklığına ve işlem süresine bağlı olarak azalmıştır. Kontrol örneklerinin yoğunluk ve EMC değerleri, ısıl işlem uygulanmış örneklere göre daha yüksek çıkmıştır. Ayrıca karaçam numunelerinde elde edilen yüzey pürüzlülük değerleri, larex numunelerine göre daha yüksektir. Öte yandan, larex numunelerinde elde edilen yapışma direnci değerleri, karaçam numunelerinden önemli ölçüde daha yüksek bulunmuştur. Ağaç işleri endüstrisindeki kullanımı sürekli olarak gelişen ısıl işlem uygulanmış ahşap malzemenin uygulama yerlerinde bu parametrelerin göz önünde bulundurulması gerekir.

Anahtar kelimeler: Isıl işlem, Yapışma direnci, Yüzey pürüzlülüğü

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*Necmettin Erbakan University, Faculty of Fine Arts and Architecture, Department of Interior Architecture and Environmental Design, Konya/Türkiye,
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1 Introduction

Wood materials are one of the most extensively used by human beings since ancient times due to their important advantages and features compared to other building materials. The fact that wood material has many unique advantages makes it attractive in many application areas. Wood material is preferred in the production of furniture and decoration elements with the effect of its natural appearance as well as its structure. In the selection of wood species, color and texture are as important as mechanical properties. However, wood material is exposed to environmental factors, biological destruction of bacteria, fungi and insects and chemical degradation such as the fire at the place of use and cannot withstand these effects for a long time (Söğütlü and Döngel, 2009). For this reason, it has become a necessity to improve the features and appearance properties of the products to be produced from wood material in order to be used for a longer period of time.

In the last few decades, researchers have attached more importance to scientific studies on the more effective and efficient use of wood materials. Environmentally friendly wood modification approaches and strategies are at the forefront of remarkable developments in this sense in recent years. Heat treatment is an environmentally friendly wood modification method that has been widely used in the last few decades to improve the properties of wood material and does not use harmful chemicals during the process (Poncsak et al. 2011; Jirouš-Rajković and Miklečić, 2019). The demand for heat treated woods has been increasing in recent years (Korkut, 2012). Heat-treated wood has many applications for exterior applications, decks, cladding, and garden furniture, including terraces, fences, doors, and window elements; as well as interior uses, such as kitchen furniture and cabinets, decorative wall panels, parquet, sauna benches and panels (Esteves and Pereira, 2009; Cui and Matsumura, 2019). Determination of the properties of heat-treated wood including surface roughness and bonding strength are important for application areas.

The surface properties of the wood material have a significant effect on the surface treatments and bonding resistance (Kilic et al. 2006). Surface roughness and wettability play an important role for better bonding strength ability of wood material (Yorur, 2018). According to literature studies show that heat treatment conditions such as treatment temperatures and treatment times were effective in changing the characteristic properties of the wood material surface. In another study, Korkut et al. (2013) carried out an experimental study to evaluate the surface roughness of heat-treated wild cherry (*Prunus avium*) wood. The test result showed that the surface roughness of the specimens decreased with heat treatment condition compared to the control samples. Korkut and Guller (2008) reported the effect of heat treatment on some properties and surface parameters of red bud maple. These authors concluded that surface parameters decreased with increasing temperature conditions. On the other hand, Söğütlü (2017) examined the effects of surface parameters on the bond resistance of wood materials. Test results showed significant differences between wood materials and also, as the surface roughness value decreased in each wood type, the bonding strength increased. Yang et al. (2012) reported that wood type and sanding processes significantly affect surface quality and adhesion resistance of wood samples. Wood surface roughness parameters may be influenced by grit size of sandpapers, heat treatment condition and machining process (Dilik and Hiziroglu, 2012; Sahin Kol and Özbay, 2016). While wood material is widely used in many applications, bonding strength plays an important role and properties related to density, grain orientation, press pressure, defects, surface quality and properties of adhesive are effective on bonding strength (Hiziroglu et al. 2013).

When the literature was examined, the mechanical features of the heat treated wood material were commonly evaluated. However little information is available on the effect of heat treatments on the surface roughness and bonding strength of wood. In addition, black pine (*Pinus nigra* A.) and lareks (*Larix decidua*) woods are widely used in construction sectors. In addition, as mentioned above the use of heat-treated wood material in the construction sector is increasing. Therefore, it is important to determine the relationship between the surface parameters of the heat-treated wood material and the adhesion strength. The purpose of this paper is to analysis the effect of heat treatment on surface roughness parameters and bonding strength of black pine (*Pinus nigra* A.) and larex (*Larix decidua*) woods.

2 Materials and Methods

2.1 Materials

In this study, black pine (*Pinus nigra* A.) and larex (*Larix decidua*) woods were preferred as experimental material. Because these woods are commonly used in woodworking industry. 650 mm by 60 mm by 18 mm defect free black pine (*Pinus nigra* A.) and larex (*Larix decidua*) samples were cut from long beams supplied by a local sawmill according to TS 2470 (1976). A total of 540 samples were used for the physical properties and bonding tests. All of the samples were held on in a climate cabinet with a relative humidity of 65 % and temperature of 20°C until they reach equilibrium moisture content before heat treatment.

Polyvinyl acetate (PVAc) adhesive was used as binder in the study, due to commonly used in the woodworking and furniture industries. In addition, this type of glue was preferred because it is widely preferred in many indoor and outdoor decoration applications. PVAc was applied to the surface of bond resistance specimens by brushing at a ratio of 180 g/m^2. PVAc has a density 1.1 g/cm^3, the viscosity is 10.000 -12.000 cPs (at 25 °C); pH value is 6-7.5 (at 25 °C) (Polisan, 2018). Samples were compressed of 1.1 N/mm^2 for 8 h for PVAc at 20 °C.

2.2 Methods

After the climatization process the test specimens were modified at 140, 160, 180 and 200 °C for 2 and 5 hours in a heat treatment furnace controlled to within ±1°C under atmospheric pressure. Before planing process, control and heat-treated samples were conditioned in a climate cabinet with a temperature of 20ºC and relative humidity of 65 %. After, specimens were processed with planing machine by four fixed-knife with a 6000 rpm spindle speed, a feed speed of 4 m/min and 1 mm cutting depth. After the planing process, the surfaces of the test samples to be measured were slightly sanded with 180 grit sandpaper sheets. In this study, the average surface roughness parameter (Ra) was used because the average roughness parameter is the most commonly used parameter for surface roughness measurements (Aydın and Çolakoğlu, 2003). Surface roughness parameter (Ra) of test samples were performed by using touch scan (spined) surface roughness device TR 200 according to TS 6956 EN ISO 4287/A1 (2013) standard.

The device (TIME-TR200) had a 10 mm/min measuring speed, a 5 μm pin radius, and a 90° probe angle. The parameters were set to a measuring step length of 2.5 mm and a measurement number of 5 (cut-off length). Measurements were carried out parallel to the fibers twice at ten different points on each specimen and the arithmetic mean value was recorded as a single value in this study. During the measurements, the device was calibrated at certain intervals. After the surface roughness measurements, the wood parts were cut in 620 mm by 60 mm by 7.5 mm dimensions for the gluing and press processes. One side of the

bonded panels was cut in the planing machine and shear test samples were prepared from them (Figure 1).

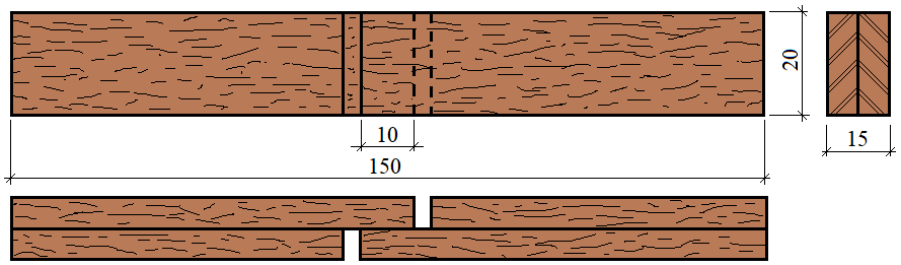

Figure 1. Bonding strength test sample and dimensions (mm)

After the preparation of tensile shear strength test samples, they were held on in a climate cabinet with a temperature of 20 °C and 65% relative humidity before tests. The bonding strength (β) was computed according to TS EN 205 (2017). The air-dried density and the equilibrium moisture content (EMC) of the samples were determined according to TS 2472 (1976), and TS 2471 (1976), respectively.

2.3 Statistical analysis

MSTAT-C statistical program was used for statistical evaluations. Multiple analyzes of variance (MANOVA) were applied. When the difference between the groups was significant according to the $P \leq 0.05$, the difference between the Duncan test and the mean values was compared. Thus, the success rankings of the factors included in the trial were determined by dividing them into homogeneity groups according to the least significant difference (LSD) critical value.

3 Results and Discussions

The equilibrium moisture content (EMC) and air-dried density value of wood samples are presented in Table 1. The density and EMC values of the control specimens were higher than the heat-treated samples. These results were statistically significant compared to the control specimens and the mean values differed significantly from each other at 0.05 confidence level. These significant changes in density and EMC values can be explained by chemical modifications after heat treatment. It is well known that the most affected wood compound by heat treatment is hemicellulose and cellulose compounds also undergo significant changes. Lengowski et al. (2021) stated that while there are significant chemical changes in wood material after heat treatment, hemicelluloses are the most affected compound. In another study, Boonstra et al (2007) mentioned that decreases in densities of woods after heat treatment, related to degradations of hemicelluloses, evaporation of extractive materials and lower equilibrium moisture content. Akyıldız and Ateş (2008) stated that the decrease in EMC values after heat treatment can be explained by the reduction of OH-groups and cleavage of the chains, as well as material losses after heat treatment. In the study by Sahin Kol et al. (2009) it was stated that the decrease in EMC values due to the decrease of total hydroxyl groups and the decrease of free hydroxyl groups related to chemical change after heat treatment. Durmaz et al. (2019) measured the changes in the physical properties of the heat treated wood whereby the density and EMC declined with increase treatment conditions. In a similar study, Bal (2015) reported that after heat treatment, the density and EMC values of wood decreased. Decreases in EMC values depending on the heat treatment temperatures were also reported by Aytin et al. 2015.

Table 1. Average density and EMC values of samples

Wood species	Heat treatment tempreature (°C)	Duration (h)	Density*		EMC**	
			Mean (g/cm^3)	SD	Mean (%)	SD
Black pine	Control	-	0.498^{J}	0.0195	13.89^{A}	0.813
	140	2	0.495^{K}	0.0161	12.23^{C}	0.683
		5	0.491^{L}	0.0158	11.44^{D}	0.613
	160	2	0.485^{M}	0.0113	10.98^{E}	0.780
		5	0.479^{O}	0.0133	10.32^{GH}	0.763
	180	2	0.481^{N}	0.0094	10.36^{G}	0.697
		5	0.473^{P}	0.0143	9.91^{IJ}	0.654
	200	2	0.461^{Q}	0.0116	9.74^{J}	0.955
		5	0.455^{R}	0.0127	9.07^{L}	0.855
Larex	Control	-	0.645^{A}	0.0174	13.49^{B}	0.901
	140	2	0.635^{B}	0.0111	12.11^{C}	0.756
		5	0.629^{C}	0.0105	11.27^{D}	0.817
	160	2	0.613^{D}	0.0116	10.76^{F}	0.865
		5	0.604^{E}	0.0129	10.11^{HI}	0.756
	180	2	0.591^{F}	0.0104	10.23^{GH}	0.713
		5	0.583^{G}	0.0139	9.41^{K}	0.867
	200	2	0.576^{H}	0.0125	8.89^{L}	0.952
		5	0.563^{I}	0.0158	8.29^{M}	0.953

*LSD: ±0.008819; **LSD: ±0.2160, Means within a column with different letters are significantly different from each other at 0.05 confidence level; SD: standard deviations

Variance analysis results for the surface roughness of the wood species, heat treatment temperature and durations are given in Table 2. According to the results in Table 2, triple interaction of wood species, treatment temperature and treatment duration on the surface roughness values were not significant, on the other hand all other factors and reciprocal interactions of these were significant ($P \leq 0.05$).

Table 2. Analysis of variance results of surface roughness value

Factors	Degrees of freedom	Sum of squares	Mean square	F Value	Sig. ($P \leq 0.05$)
Wood species (A)	1	235.011	235.011	14738.3507	0.0000*
Treatment temperature (B)	4	35.946	8.986	563.5739	0.0000*
Interaction (AB)	4	1.501	0.375	23.5301	0.0000*
Treatment duration (C)	1	1.186	1.186	74.3655	0.0000*
Interaction (AC)	1	0.168	0.168	10.5484	0.0014*
Interaction (BC)	4	0.359	0.090	5.6317	0.0003*
Interaction (ABC)	4	0.049	0.012	0.7651	NS
Error	160	2.870	0.018		
Total	179	277.090			

NS: not significant; * Significant at 95 % confidence level

Single comparison results of the Duncan test conducted on surface roughness using least significant difference (LSD) critical values for wood species, treatment temperature and

treatment duration level are given in Table 3. Based on the results in Table 3, the surface roughness values obtained in black pine samples were higher than larex samples. The differences between roughness parameters can be explained by the density properties of the wood materials. According to Table 1, density values of larex samples higher than black pine samples. In addition, black pine samples had a more porous anatomy compared to larex specimens. The differences of the values of surface roughness for different wood species could also be explained by the influence of the wood texture (Thoma et al. 2015). In the literature, the decrease in surface roughness with increasing density has been noted in the previous study by Pinkowski et al (2018) stated that the density highly affects the surface roughness parameters and that the increase in wood density decreases the surface roughness. Many different factors such as surface treatment direction, density, wood type, chemical and anatomical structure of wood, moisture content, cutter type, cutting feed rate and depths, the heat treatment temperature etc. play a role in the surface roughness values of the wood material (Baysal et al. 2014; Pelit et al. 2015; Ayata et al. 2018; Bal and Gündeş, 2020; Aras and Sofuoglu, 2021; Rohumaa et al. 2021; Sofuoglu, 2021).

Table 3. Results of Duncan test related to surface roughness at wood species, heat treatment, and heat treatment durations

Factors	Surface roughness (μm)
Wood species*	
Black pine	7.814^{A}
Larex	5.646^{B}
Heat treatment (°C)**	
Control	7.305^{A}
140	7.120^{B}
160	6.660^{C}
180	6.355^{D}
200	6.210^{E}
Duration (h)***	
2	6.807^{A}
5	6.653^{B}

*LSD: ±0.03528; **LSD: ±0.05578; ***LSD: ±0.03528

Regarding the heat treatment temperature, the highest surface roughness value (7.305 μm) was obtained in the control samples, whereas the lowest (6.210 μm) was determined in the samples that heat treated at 200°C. Surface roughness parameters decreased depending on the increase of treatment conditions. In a previous study by Ozcan et al. (2012) stated that in heat treatment applied above 150 – 160°C, gave rise to conversion of lignin and thermoplastic condition developing densification of the surface layers, and this situation contributed to the development of surface roughness values. Korkut and Guller (2008) examined effects of heat treatment on surface roughness of wood. They reported that the value of surface parameters decreased with increase treatment temperatures and treatment time. Considering the applied heat treatment time, the surface roughness value of the applied heat treatment time at 5 h was higher than 2 h. According to this result, it can be said that the applied heat treatment time was also effective in the surface roughness values as well as the applied heat temperature in this study. In a similar study, Korkut and Budakci (2010) reported that the surface roughness value of heat-treated wood samples decreased as the heat treatment time increased.

The surface roughness values of black pine (*Pinus nigra* A.) and larex (*Larix decidua*) woods are presented comparatively in Figure 3.

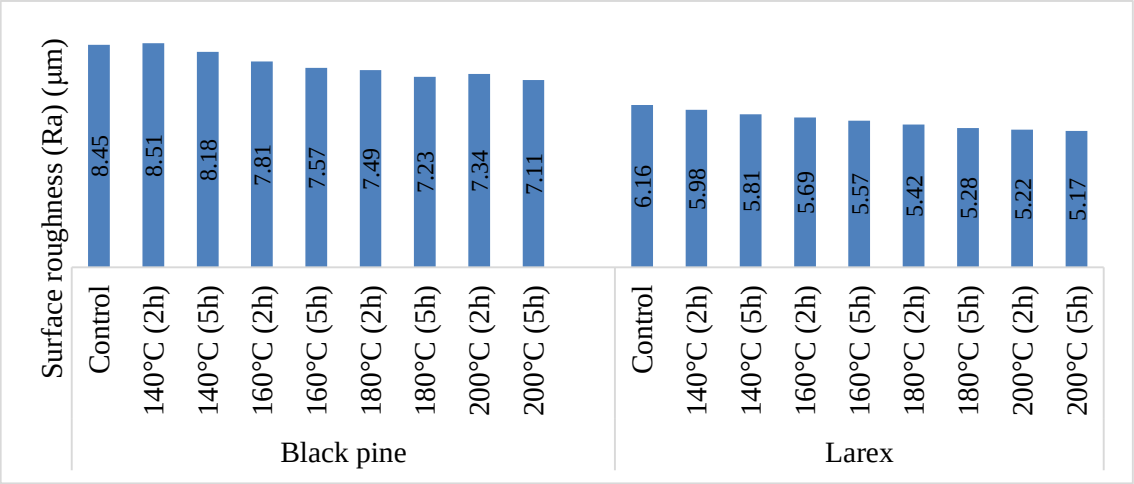

Figure 3. Average roughness values of the samples

According to the Figure 3, average Ra value of the samples from 8.51 µm to 7.11 µm for black pine samples, while from 6.16 µm to 5.17 µm for larex samples. According to these results, for both wood samples, the roughness values decreased as the heat treatment temperature and time increased. The results shown in Figure 3, indicated that the lowest surface roughness value was measured in samples that were heat treated at 200 °C for 5 hours (7.11 µm), while the highest was measured in samples that were heat treated at 140 °C for 2 hours (8.51µm) for black pine samples. Regarding the larex samples, the highest surface roughness value was determined in control samples (6.16 µm), while the lowest value was measured in specimens that were heat treated at 200 °C for 5 hours (5.17 µm).

Variance analysis results for the bonding strength of the wood species, heat treatment temperature and durations are given in Table 4. According to Table 4, effects of wood species, heat treatment temperature, and treatment time; dual interaction of wood species-treatment temperature; dual interaction of wood species-treatment time; dual interaction of treatment temperature-treatment time and triple interaction of wood species, treatment temperature and treatment time on the bonding strength values were significant whereas another interaction was insignificant ($P \leq 0.05$).

Table 4. Analysis of variance results of bonding strength value

Factors	Degrees of	Sum of	Mean	F	Sig.
Wood species (A)	1	386.812	386.812	820.9328	0.0000*
Treatment temperature (B)	4	104.811	26.203	55.6102	0.0000*
Interaction (AB)	4	22.382	5.596	11.8754	0.0000*
Treatment duration (C)	1	4.886	4.886	10.3688	0.0015*
Interaction (AC)	1	0.227	0.227	0.4822	Ns
Interaction (BC)	4	11.432	2.858	6.0658	0.0001*
Interaction (ABC)	4	4.578	1.144	2.4289	0.0494*
Error	160	84.813	0.530		
Total	179	619.942			

Ns: not significant; * Significant at 95 % confidence level

Single comparison results of the Duncan test conducted on bonding strength using least significant difference (LSD) critical values for wood species, treatment temperature and treatment duration level are given in Table 5.

Table 5. Duncan test results for bonding strength at wood species, heat treatment, and heat treatment durations level

Factors	Bonding strength (N/mm^2)
Wood species*	
Black pine	9.757^B
Larex	12.54^A
Heat treatment (°C)**	
Control	12.02^A
140	11.85^A
160	11.17^B
180	10.58^C
200	10.13^D
Duration (h)***	
2	11.30^A
5	10.99^B

*LSD: ±0.1914; **LSD: ±0.3026; ***LSD: ±0.1914

It can be seen from Figure 4 and Table 5 that the bonding strength value obtained in larex samples was significantly higher than that of black pine samples. This situation can be explained by high density values and surface roughness parameters of larex samples. In the literature, wood materials with low surface roughness values have higher bonding strength compared to rougher surfaces (Buyuksari et al. 2011; Söğütlü, 2017). Kaygin and Tankut (2008) reported that the lowest bonding strength value was due to cell structure of wood and its over porosity structures. Based on the findings in this study bonding strength of the samples were adversely influenced due to heat treatment temperature and treatment durations. According to Table 5, the highest bonding strength value was determined in control samples, regarding the heat treatment temperature, while the lowest in specimens that were heat treated at 200 °C. A similar study by Ozcan et al. (2012) indicated that especially with high temperature heat treatment, adhesion resistance is significantly reduced due to the degradation of hemicellulose in the wood cell wall structure. Can et al. (2021) reported in their study that shear strength decreased significantly after heat treatment and that reduced chemical bonding or mechanical interlocking of adhesives, and the reduced strength of the brittle heat-treated wood might be responsible for this.

In terms of the heat treatment time, the bonding strength decreased as the treatment time increased in this study. The bonding strength of specimens that heat-treated for two hours was higher than that of heat treated wood for five hours. In the literature, some studies reported that the bonding performance of the wood is negatively affected by the higher temperature and treatment time (Hill, 2006; Ayrilmis and Winandy, 2008). The bonding strength values of black pine (*Pinus nigra* A.) and larex (*Larix decidua*) samples are presented comparatively in Figure 4.

According to the data in Figure 4, bonding strengths of heat-treated samples were lower as compared to those of control samples. Bonding strength values decreased in both wood species depend on the increase in heat treatment temperatures and treatment times. The highest bonding strengths were determined in the control groups for black pine (10.62 N/mm^2) and larex (13.89 N/mm^2) samples. It is a well-known fact that density properties and anatomical structures of wood material play an important role on physical and mechanical properties including bonding strength. Bonding features and bonding strengths are affected by many factors such as wood types and their densities, adhesive type and its viscosity, press pressure, press temperature and time, moisture content of wood, compression ratio of the veneers, etc. (Yorur et al. 2010; Bekhta et al. 2020).

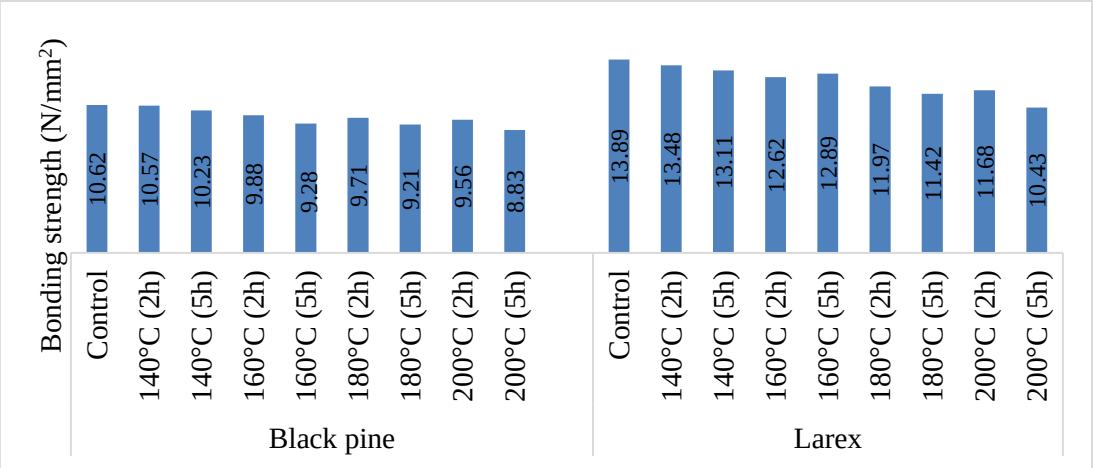

Figure 4. Average bonding strength values of the samples

4 Conclusions

Based on the study, the following conclusions can be made:

- The test results revealed that the values of density, equilibrium moisture content, surface roughness and bonding strength of black pine (*Pinus nigra* A.) and larex (*Larix decidua*) samples decreased depending on increasing treatment temperature and treatment times. Therefore, this situation should be considered in the places of use of heat treated wood materials.
- In terms of surface roughness value, larex wood was lower than black pine. Surface roughness properties are one of the most important parameters in the woodworking and furniture industries.
- Regarding the bonding strength, black pine specimens had lower values than that of larex samples. The bonding quality and bonding strength of wood material are important for structural and outdoor applications.
- Wood species and heat treatment conditions significantly influence on surface roughness and bonding strength.

Author Contributions

Osman Perçin: Research idea, planning and conducting laboratory studies, obtaining data, analysis data, writing the manuscript, publishing the manuscript.

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