

# THE EFFECTS OF DENSIFICATION AND HEAT TREATMENT ON THERMAL CONDUCTIVITY OF FIR WOOD

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**Abstract:** The goal of this study was to determine the effect of densification and heat treatment on thermal conductivity properties of fir (*Abies bornmulleriana* Mattf.) wood. Fir wood specimens were densified with compression ratios of 25% and 50%, and at 100 °C or 140 °C. Then, the heat treatment was applied to the fir specimens at 185 °C and 212 °C for 2 hours according to ThermoWood® method. The study results showed that, densification and thermal treatment applications was effected thermal conductivity of the fir specimens. The thermal conductivity increased based on compression ratios and temperatures in the densified specimens. The thermal conductivity in the compressed specimens at high ratio (50%) was found higher than other specimens. After densification, additionally, thermal conductivity increasing on the radial surface was higher compared to the tangential surface. After heat treatment, thermal conductivity of the all specimens decreased significantly depending on the increase in treatment temperature. Particularly, the heat-treated fir specimens at 212 °C may considered where thermal insulation is important.

**Keywords:** Fir Wood, Densification, Heat Treatment, Thermal Conductivity

## Introduction

The properties of wood depend on its chemical and structural characteristics. These can be changed using different and/or new wood modification techniques. Thus, wood can be made more resistant to destructive environmental factors (Bami and Mohebbi, 2011). The mechanical properties of wood positively correlate with its density, and the mechanical strength can be improved by increasing the density. An increment of density is particularly important for low-density wood species (Laine et al., 2013; Sandberg et al., 2013). Wood can be densified by applying mechanical high-pressure compression with heat and/or steam. In addition, wood can be densified by saturating its pore volume with natural or synthetic resins (Kamke, 2006; Kutnar et al., 2008). A main disadvantage of mechanically densified wood is the recovery of its initial dimensions after exposure to water or heat (Seborg et al., 1956; Morsing, 2000; Blomberg et al., 2006; Pelit et al., 2014, 2016). One of the wood modification processes whose usage is increasing day to day and which are performed for extending their usage fields by enhancing some properties (stability, durability, etc.) of wood, is heat-thermal treatment.

The heat treatment process results in a modification in the molecular structure of the wood and thus improves its performance. The properties potentially improved by heat treatment are: biological resistance to fungi and insects, low equilibrium moisture content, increased dimensional stability with respect to the decrease in contraction and expansion, increased resistance to weathering, and increased thermal insulation capacity (Korkut and Kocaeffe, 2009). On the other hand, the density and mechanical strength properties of heat-treated wood decrease due to mass loss and thermal degradation of the wood structure (Bekhta and Niemz 2003; Yıldız et al. 2006; Korkut et al., 2008; Pelit et al., 2015; Perçin et al., 2015). The decline in the strength properties of wood is the primary disadvantage of the heat treatment application. This situation restricts the sectors in which heat-treated wood may be used (Boonstra 2008).

As it is known, wood material that has a wide usage area as a natural raw material is a good insulator because of its structure (Aytin et al., 2016). Thermal conductivity of a material can be defined as the rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference. The thermal conductivity of a material is a measure of how fast heat will flow in that material. A large value of a thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or insulator (Şahin Kol and Sefil, 2011). The thermal properties of wood are affected by various factors. The more important influencing factors are species, density, moisture content, direction of heat flow (anisotropy), inclination of grain, and relation of volume or thickness of the sample to moisture content (Suleiman et al., 1999). In addition,

have an influence on thermal conductivity of wood material factors like kiln-drying operations, glueing of wood, preservation impregnation, hot pressing of wood based composites, and wood thermal degradation (Şahin Kol, 2009). In light of literature informations, the purpose of this study was to determine the thermal conductivity properties of the fir (*Abies bornmulleriana* Mattf.) wood specimens modified by densification and heat post-treatment applying.

## Materials and Methods

### *Wood material*

In this study, Uludağ fir (*Abies bornmulleriana* Mattf.) wood were used. The fir tree were supplied as logs from a lumber yard in Düzce, Turkey. The sapwood was cut from the logs with an automatically controlled band saw. Rough-scale planks were formed, the cuts being determined by considering the annual rings parallel to the surface (tangent section) and the sample dimensions. Attention was paid to ensure that no rot, knot, crack, color, or density differences were present in the specimens (TS 2470, 1976). The specimens were initially subjected to natural drying to approximately 12% moisture content, and then were cut to the dimensions of 420 × 95 mm (length-longitudinal direction × width-tangential direction) and two different thicknesses 26.7 and 40 mm (radial direction). Before the densification process, the specimens were held in a conditioning cabin (RH 65 ± 3% and 20 ± 2 °C) until they reached a stable weight (TS 2471, 1976).

### *Thermo-mechanical densification and heat treatment*

The thermo-mechanical densification process was done with a hydraulic press at compression ratios of 25 and 50%, with temperatures of 100 and 140 °C for 10 min. After thermo-mechanical densification, heat post-treatment was carried out on the wood specimens to provide dimensional stability. The heat treatment was conducted under the protection of water vapor at the temperatures 185 and 212 °C for 2 h. The thermo-mechanical densification and heat post-treatment processes have been described in detail in a previous study by the authors (Pelit et al., 2016). After heat post-treatment, specimens remained in a conditioning cabin (RH 65 ± 3% and 20 ± 2 °C) until they reached a stable weight (TS 2471, 1976). The densified and heat treated specimens were then cut into smaller specimens in the dimensions of 100 × 20 × 20 mm<sup>3</sup> (longitudinal direction × tangential direction × radial direction). Test specimens were prepared in a number sufficient to accommodate 10 repetitions (*n*=10) for each variable.

### *Measurement of thermal conductivity*

Thermal conductivity values of fir specimens was determined according to ASTM C 1113-99 (2004) by using hot-wire method. Measurements were made using QTM 500 (Quick Thermal Conductivity) device which is a product of Kyoto Electronics Manufacturing, Japan. PD-11 box probe sensor (constantan heater wire and chromel-alumel thermocouple) was used. After the completion of the device calibration, measurements performed on the surface of each sample for a period of one minute.

### *Statistical analyses*

The MSTAT-C package program was used for statistical evaluations. Analysis of variance (ANOVA) was performed between factors, and differences between Duncan test results and mean values were compared when significant differences were detected within obtained data. Therefore, success ranking among the factors included into the experiment was determined by separating them into homogeneous groups according to Least Significant Difference (LSD) critical values.

## Results and Discussion

Analysis of variance results of thermal conductivity values of fir wood specimens thermo-mechanically densified and heat treated are given in Table 1.

**Table 1:** Analysis of variance results for thermal conductivity values

Factors	Degrees of freedom	Sum of squares	Mean square	F-value	Level of significance ( $P \leq 0.05$ )
Measuring surface (A)	1	0.007	0.007	200.2131	0.0000*
Densification (B)	4	0.028	0.007	189.6054	0.0000*
Interaction (AB)	4	0.010	0.002	66.7987	0.0000*
Heat treatment (C)	2	0.070	0.035	947.1696	0.0000*
Interaction (AC)	2	0.000	0.000	5.0091	0.0073*
Interaction (BC)	8	0.001	0.000	2.6475	0.0082*

Interaction (ABC)	8	0.001	0.000	4.8366	0.0000*
Error	270	0.010	0.000		
Total	299	0.128			

\*Significant at 95% confidence level

According to analysis of variance results; measuring surface, densification, and heat treatment factors on thermal conductivity values of fir wood specimens and their reciprocal interactions were found to be significant ( $P \leq 0.05$ ). Mono comparison results of Duncan test, which was conducted by using LSD critical value at measuring surface, densification and heat treatment level, are shown in Table 2.

**Table 2:** Mono comparison results of Duncan test for thermal conductivity values at measuring surface, densification and heat treatment level

Measuring surface	Mean	HG	<i>LSD</i> ± 0.002273
Tangential section	0.1280	b	
Radial sections	0.1379	a*	
Densification	Mean	HG	<i>LSD</i> ± 0.003595
Undensified	0.1172	e	
100 °C / 25%	0.1291	d	
100 °C / 50%	0.1410	b	
140 °C / 25%	0.1327	c	
140 °C / 50%	0.1448	a*	
Heat treatment	Mean	HG	<i>LSD</i> ± 0.002784
Untreated	0.1497	a*	
185 °C	0.1365	b	
212 °C	0.1127	c	

HG: Homogeneous group; \*: the highest value

According to the results of the comparisons in Table 3, thermal conductivity value of fir wood specimens was higher in radial sections (0.1379) than tangential section (0.1280). Regarding densification conditions, the highest thermal conductivity value (0.1448) was found in the specimens densified by compression 50% at 140 °C and the lowest (0.1172) in the undensified specimens. As for the heat treatment level, the highest thermal conductivity value (0.1497) was seen in the untreated specimens, while the lowest (0.1127) was in the specimens subjected to heat treatment at 212 °C. Multiple comparison results of the Duncan test conducted by using the LSD critical value at measuring surface-densification-heat treatment trio interaction level are given in Table 3.

**Table 3:** Comparison results of Duncan test for thermal conductivity values at measuring surface-densification-heat treatment trio interaction level

Densification	Heat treatment	Measuring surface					
		Tangential section			Radial sections		
		Mean	SD	HG	Mean	SD	HG
Undensified	Untreated	0,1393	0,007	hi	0,1324	0,008	ijk
	185 °C	0,1243	0,004	kl	0,1114	0,004	no
	212 °C	0,1019	0,003	pq	0,0937	0,002	q
100 °C / 25%	Untreated	0,1406	0,009	ghu	0,1524	0,008	cde
	185 °C	0,1298	0,004	jkl	0,1333	0,006	ij
	212 °C	0,1046	0,007	op	0,1140	0,006	mn
100 °C / 50%	Untreated	0,1552	0,009	bcd	0,1591	0,006	abc
	185 °C	0,1424	0,004	fgh	0,1489	0,004	defg
	212 °C	0,1140	0,002	mn	0,1262	0,002	jkl

140 °C / 25%	Untreated	0,1445	0,008	efgh	0,1559	0,008	bcd
	185 °C	0,1212	0,003	lm	0,1496	0,003	def
	212 °C	0,1032	0,008	op	0,1215	0,003	lm
140 °C / 50%	Untreated	0,1506	0,009	cdef	0,1669	0,008	a*
	185 °C	0,1404	0,004	ghi	0,1635	0,008	ab
	212 °C	0,1078	0,004	nop	0,1400	0,006	hi

*LSD*: ± 0.008805

SD: Standard deviation; HG: Homogeneous group; \*: the highest value

According to results shown in Table 3, the highest thermal conductivity value (0.1669) was obtained in radial section of specimens without heat treatment that were densified by compression 50% at 140 °C, and the lowest value (0.0937) was obtained in radial section of the specimens for which heat treatment was applied at 212 °C and they were undensified. Thermal conductivity values of densified specimens increased depending on compression ratio and temperature. Thermal conductivity values was highest at each measured section of 50% compressed specimens. In terms of compression temperature, the highest thermal conductivity values was obtained from specimens compressed at 100 °C for the tangential section and specimens compressed at 140 °C for radial section. After compressing process, the thermal conductivity values increased up to %11 on tangential section and up to %26 on the radial section compared with control specimens. The higher increase of thermal conductivity on the radial section (surface) is related with compression of specimens at radial direction. In addition, the increase of thermal conductivity can be explained by decrease of void volume (porosity) and increase of density of fir specimens. In the densification process, it was determined in previous studies that the void volume of wood decreased and the amount of cell wall per unit volume increased according to compression ratio (Blomberg et al., 2005; Ünsal et al., 2011; Ülker et al., 2012; Arruda and Menezzi, 2013; Pelit et al., 2014). The thermal conductivity of wood is closely related with the density and porosity. It was reported that thermal conductivity increases proportionally with density and increases in inverse proportion to the porosity (Suleiman et al., 1999; Rice and Shepard, 2004; Şahin Kol et al., 2008; Örs and Keskin, 2008).

Thermal conductivity decreased in all heat treated specimens. In addition, the increase in the temperature of the heat treatment significantly decreased thermal conductivity values. However, the thermal conductivity values of densified (especially on the radial section) specimens influenced less by the application of heat treatment than control specimens. In the previous studies conducted in parallel to this study, it was determined that the values of equilibrium moisture content (Pelit et al., 2016) and air-dry density (Pelit et al., submitted for publication) of heat-treated fir wood specimens decreased depending on the increase of heat. In addition, it was reported that the hygroscopicity, equilibrium moisture content (EMC) and density of heat-treated specimens decreased (Tjeerdsma and Militz, 2005; Esteves et al., 2007; Boonstra, 2008; Esteves and Pereira, 2009; Korkut and Kocaefe, 2009; Aydemir et al., 2011; Pelit et al., 2014; Aytin et al., 2015; Kocaefe et al., 2015). After heat treatment process, the significant decrease in the thermal conductivity values can be explained by the reduction in the EMC and density. The results are compatible with the literature (Şahin Kol and Sefil, 2011; Aytin et al., 2016). In literature stated that there is a very strong correlation between moisture content and thermal conductivity and the thermal conductivity increases with increasing moisture content. Because the thermal conductivity of water is much higher than wood (Gu and Hunt, 2007; Şahin Kol, 2009; Şahin Kol and Sefil, 2011).

## Conclusion

After densification process, thermal conductivity values of fir specimens increased depending on the compression ratio and temperature. The thermal conductivity values was higher in the specimens compressed at high ratio (50%). In terms of compression temperature, the highest thermal conductivity values was obtained from specimens compressed at 100 °C for the tangential section and specimens compressed at 140 °C for radial section. The thermal conductivity values of densified specimens increased up to 11% on tangential section and up to 26% on the radial section compared with control specimens. After heat treatment process, thermal conductivity values of all specimens decreased significantly depending on the increase of the process temperature. However, the thermal conductivity values of densified specimens (particularly in the radial section) influenced less by the application of heat treatment compared with control specimens.

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