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

Hüseyin PELİT[a,*], Mustafa KORKMAZ[a], Mehmet BUDAKÇI[a], Raşit ESEN[b]

[a] Duzce University, Faculty of Technology, Department of Wood Products Industrial Engineering, Duzce-Turkey
[b] Karabuk University, Faculty of Fine Arts, Department of Industrial Design, Karabuk-Turkey

*Corresponding author: huseyinpelit@duzce.edu.tr

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 ºC and 212 ºC 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 considerated 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 Mohebby, 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 Kocaefe, 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^3 (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	
Tangential section	0.1280	b	*LSD* ± 0.002273
Radial sections	0.1379	a*	
Densification	**Mean**	**HG**	
Undensified	0.1172	e	*LSD* ± 0.003595
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**	
Untreated	0.1497	a*	*LSD* ± 0.002784
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 ºC 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 ºC. 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	hı	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	ghı	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	ghı	0,1635	0,008	ab
	212 ˚C	0,1078	0,004	nop	0,1400	0,006	hı

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 ºC, and the lowest value (0.0937) was obtained in radial section of the specimens for which heat treatment was applied at 212 ºC 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 conducitivity 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 conducitivity 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 denfication process, it was determinated 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 conductiviy 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 conducitivity values of densified (especially on the radial seciton) 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, equilibruim moisture content (EMC) and density of heat-treated specimens decreased (Tjeerdsma and Militz, 2005; Esteveset 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 precess, 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 conducitivity values of densified specimens (particularly in the radial section) influenced less by the application of heat treatment compared with control specimens.

References

ASTM C 1113-99 (2004), Standart test for thermal conductivity of refractories by hot wire (Platinum Resistanca Thermometer technique), *American Society for Testing and Materials International*, West Consokocken.

Arruda, L. M., & Del Menezzi, C. H. (2013). Effect of thermomechanical treatment on physical properties of wood veneers. *International Wood Products Journal* 4(4), 217-224.

Aydemir, D., Gündüz, G., Altuntaş, E., Ertas, M., Şahin, H. T., & Alma, M. H. (2011). Investigating changes in the chemical constituents and dimensional stability of heat-treated hornbeam and Uludağ fir wood. *BioResources* 6(2), 1308-1321.

Aytin, A., Korkut, S., Ünsal, Ö., & Çakıcıer, N. (2015). The effects of heat treatment with the ThermoWood® method on the equilibrium moisture content and dimensional stability of wild cherry wood. *BioResources* 10(2), 2083-2093.

Aytin, A., Korkut, S., & Şahin Kol, H. (2016). The effect of heat treatment on insulating properties in wooden material. *Journal of Advanced Technology Sciences* 5(1), 173-180.

Bami, L.K., & Mohebby, B. (2011). Bioresistance of poplar wood compressed by combined hydro-thermo-mechanical wood modification (CHTM): Soft rot and brown-rot. *International Biodeterioration & Biodegradation* 65(6), 866-870.

Bekhta, P., & Niemz, P. (2003). Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood. *Holzforschung* 57(5), 539-546.

Blomberg, J., Persson, B., & Blomberg, A. (2005). Effects of semi-isostatic densification of wood on the variation in strength properties with density. *Wood Science and Technology* 39(5), 339-350.

Blomberg, J., Persson, B., &Bexell, U. (2006). Effects of semi-isostatic densification on anatomy and cell-shape recovery on soaking. *Holzforschung* 60(3), 322-331.

Boonstra, M.J. (2008). *A two-stage thermal modification of wood*. Ph.D. dissertation, Co-supervised by Ghent University, Ghent, Belgium, and Université Henry Poincaré, Nancy, France.

Esteves, B., Velez, M.A., Domingos, I., & Pereira, H. (2007). Influence of steam heating on the properties of pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) wood. *Wood Science Technology* 41(3), 193-207.

Esteves, B.M., & Pereira, H.M. (2009). Wood modification by heat treatment: A review. *BioResources* 4(1), 370-404. DOI: 10.15376/biores.4.1.370-404

Gu, H.M., & Hunt, J.F. (2007). Two-dimensional finite element heat transfer model of softwood. part III. effect of moisture content on thermal conductivity. *Wood and Fiber Science* 39 (1), 159-166.

Kamke, F. A. (2006). Densified radiata pine for structural composites. *Maderas. Ciencia y tecnologia* 8(2), 83-92.

Kocaefe, D., Huang, X., & Kocaefe, Y. (2015). Dimensional stabilization of wood. *Current Forestry Reports* 1(3), 151-161.

Korkut, S., Kök, M.S., Korkut, D.S., & Gürleyen, T. (2008). The effects of heat treatment on technological properties in red-bud maple (*Acer trautvetteri* Medw.) wood. *Bioresource Technology* 99(6), 1538-1543.

Korkut, S., & Kocaefe, D. (2009). Effect of heat treatment on wood properties. *Düzce University, Journal of Forestry* 5(2), 11-34.

Kutnar, A., Kamke, F.A., & Sernek, M. (2008). The mechanical properties of densified VTC wood relevant for structural composites. *Holz als Roh-und Werkstoff* 66(6), 439-446.

Laine, K., Rautkari, L., & Hughes, M. (2013). The effect of process parameters on the hardness of surface densified Scots pine solid wood. *European Journal of Wood & Wood Products* 71(1), 13-16.

Morsing, N. (2000). *Densification of Wood - The Influence of Hygrothermal Treatment on Compression of Beech Perpendicular to the Grain*, Ph.D. Dissertation, Technical University of Denmark, Lyngby, Denmark.

Örs, Y., & Keskin, H. (2008). Ağaç malzeme teknolojisi. *Öz Baran Ofset Matbaacılık*, Ankara, Turkey.

Pelit, H., Sönmez, A., & Budakçı, M. (2014). Effects of ThermoWood® process combined with thermo-mechanical densification on some physical properties of Scots pine (*Pinus sylvestris* L.). *BioResources* 9(3), 4552-4567.

Pelit, H., Sönmez, A., & Budakçı, M. (2015). Effects of thermomechanical densification and heat treatment on density and Brinell hardness of Scots pine (*Pinus sylvestris* L.) and Eastern beech (*Fagus orientalis* L.). *BioResources* 10(2), 3097-3111.

Pelit, H., Budakçı, M., & Sönmez, A. (2016). Effects of heat post-treatment on dimensional stability and water absorption behaviours of mechanically densified Uludağ fir and black poplar woods. *BioResources* 11(2), 3215-3229.

Pelit, H., Budakçı, M., & Sönmez, A. (submitted for publication). Density and some mechanical properties of densified and heat post-treated uludağ fir, linden and black poplar woods. *European Journal of Wood & Wood Products*

Perçin, O., Sofuoğlu, S. D., & Uzun, O. (2015). Effects of boron impregnation and heat treatment on some mechanical properties of oak (*Quercus petraea* Liebl.) wood. *BioResources* 10(3), 3963-3978.

Rice, R.W., & Shepard R. 2004. The thermal conductivity of plantation grown white pine (*Pinus stropus*) and red pine (*Pinus resinosa*) at two moisture content levels. *Forest Products Journal* 54 (1), 92-94.

Sandberg, D., Haller, P., & Navi, P. (2013). Thermo-hydro and thermo-hydro-mechanical wood processing - An opportunity for future environmentally friendly wood products. *Wood Material Science & Engineering* 8(1), 64-88.

Seborg, R. M., Millett, M. A., & Stamm, A. J. (1956). Heat-stabilized compressed wood (Staypak). F.P.L., Report No: 1580 (revised).

Suleiman, B.M., Larfeldt, J., Leckner, B., & Gustavsson, M. (1999). Thermal conductivity and diffusivity of wood. *Wood Science and Technology*, 33 (6), 465-473.

Şahin Kol, H., Özçifçi, A., & Altun, S. (2008). Effect of some chemicals on thermal conductivity of laminated veneer lumbers manufactured with urea formaldehyde and phenol formaldehyde adhesives. *Kastamonu University Journal of Forestry Faculty 8*(2), 125-130.

Şahin Kol, H. (2009). Thermal and dielectric properties of pine wood in the transverse direction. *BioResources* 4 (4), 1663-1669.

Şahin Kol, H., & Sefil, Y. (2011). The thermal conductivity of fir and beech wood heat treated at 170, 180, 190, 200, and 212°C. *Journal of Applied Polymer Science* 121(4), 2473–2480.

Ülker, O., İmirzi, Ö., & Burdurlu, E. (2012). The effect of densification temperature on some physical and mechanical properties of Scots pine (*Pinus sylvestris* L.). *Bioresources* 7(4):5581-5592.

Ünsal, Ö., Candan, Z., Büyüksarı, Ü., Korkut, S., Chang, Y. S., & Yeo, H. (2011). Effect of thermal compression treatment on the surface hardness, vertical density propile and thickness swelling of eucalyptus wood boards by hot-pressing. *Mokchae Konghak* 39(2), 1-8.

Tjeerdsma, B., & Militz, H. (2005). Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood. *Holz als Roh- und Werkst* 63(2), 102-111.

TS 2470. (1976). Sampling methods and general requirements for physical and mechanical tests in wood. Turkish Standards Institute, Ankara, Turkey.

TS 2471. (1976). Determination of moisture content for physical and mechanical tests in wood. Turkish Standards Institute, Ankara, Turkey.

Yıldız, S., Gezer, E. D., & Yıdız, Ü. C. (2006). Mechanical and chemical behavior of spruce wood modified by heat. *Building & Environment* 41(12), 1762-1766.