Thermal Conductivity Temperature Dependence of Heat-treated Wood at Different Moisture Content Levels

Hamiyet Şahin Kol,[a] and Kübra Gündüz Vaydoğan [b,*]

Effects of temperature dependence and relative humidity were studied relative to the thermal conductivity of heat-treated pine and heat-treated beech, which are frequently used for building construction. Pine and beech wood were exposed to heat treatment at 180, 200, and 220 °C in nitrogen gas for 2 h. As a result, the thermal conductivity values of the heat-treated wood decreased as the temperature of the heat treatment process increased and relative humidity increased. However, thermal conductivity of wood became more stable after heat treatment under relative humidity changes. The thermal conductivity values increased with rising mean plate temperatures, while the temperature dependence of the heat-treated wood was not affected by the relative humidity changes. Consequently, heat-treated wood, with variable humidity without excessive heat changes, can be preferred for the construction of buildings.

DOI: 10.15376/biores.18.3.5253-5268

Keywords: Thermal conductivity; Heat treatment; Moisture content; Pine; Beech

*Contact information: a: Department of Environmental Engineering, Karabuk University, P. O. Box 78200, Karabuk, Turkey; b: Department of Forest Industrial Engineering, Karabuk University, P. O. Box 78200, Karabuk, Turkey; *Corresponding author: kubragunduz@karabuk.edu.tr*

INTRODUCTION

Heat treatment modification of wood is usually carried out at temperatures between 160 and 240 °C, and various external variables (temperature, duration, type, and composition of the surrounding atmosphere) influence the chemical changes that occur all over the treatment process. Heat treatment provides certain advantages in terms of reducing wood hygroscopicity, enhancing wood dimensional stability, and boosting biological durability (Rowell *et al*. 2009; Sandberg *et al*. 2013; Nasir *et al*. 2018; Kamperidou 2019; Fu *et al*. 2019).

Nowadays, due to these great features, heat-treated wood is extensively preferred in non-structural modern building construction, including exterior cladding, terraces, windows, flooring, stair treads, kitchen floors, bathrooms, and saunas (Gündüz *et al*. 2008; Sandberg and Kutnar 2016; Herrera *et al*. 2018). The most attractive property of heat-treated wood is its low hygroscopicity, which broadens its applications, particularly in the building industry. Decorative color options are another advantage for consumers, as the natural color of the wood is dark after heat treatment (Esteves *et al*. 2007; Aydemir and Gündüz 2009; Esteves and Pereira 2009). The dimensional stability of wood is affected by hygroscopicity, which also reduces the risk of fungal and insect attacks (Kandem *et al*. 2002; Yıldız *et al*. 2006; Kocaefe *et al*. 2008; Kamperidou 2019). As a result, the longevity of a wooden structure is directly correlated with the hygroscopicity of wood. Heat-treated wood with low hygroscopicity can be used more efficiently throughout its life in buildings without experiencing any dimensional movement problems due to possible changes in the humidity in the environment (Priadi and Hıziroğlu 2013). In addition, hygroscopic hysteresis of wood increases with heat treatment (Fu *et al.* 2019). The mass loss of wood during heat treatment is one of the most crucial features in thermal modification, and it is commonly used as an indicator of heat treatment intensity (Hill 2006; Candelier *et al.* 2016). The thermal treatment reduces the wood's volume and mass, but since the latter is more intense, the density also decreases (Pásztory *et al*. 2017). However, some major drawbacks of heat treatment include weakening the wood's overall strength and stiffness and making it more brittle (Czajkowski *et al*. 2020).

Nowadays, thermal insulation is becoming more important in the construction of new buildings, as energy becomes more precious and demand rises (Coman *et al.* 2017). Thermal efficacy is primarily determined by a material's *k*-value, which is defined as the heat transfer rate through a unit thickness of the material per unit area per unit temperature difference (Sahin Kol and Sefil 2011). A material's *k*-value is influenced by density, porosity, moisture content, and mean temperature difference. The thermal load, and thus the energy consumption, of a building can be considerably decreased by using materials with low thermal conductivity (*k*-value) (Budaiwi and Abdou 2013; Cavus *et al*. 2019). As the usage of heat-treated wood in buildings has grown in popularity, so has research into its thermal qualities. Numerous studies have been carried out to assess the heat treatment on the thermal conductivity (*k*-value) of wood (Sahin Kol and Sefil 2011; Korkut *et al.* 2013; Olarescu *et al.* 2015; Aytin *et al.* 2016; Sahin Kol and Aysal Keskin 2016; Pasztory *et al.* 2017; Pelit *et al.* 2017; Czajkowski *et al*. 2020). It has been hypothesized that the structural and chemical change brought about by heat treatment could potentially impact its *k*-value. The *k*-value is reduced after heat treatment, but how much was found to depend on thermal treatment duration and temperature (Kol and Sefil 2011; Olarescu *et al.* 2015; Pásztory *et al.* 2017; Pasztory *et al.* 2018; Srivaro *et al.* 2019; Czajkowski *et al.* 2020; Čabalová *et al.* 2022).

Several studies have examined the impact of operation temperature on the thermal performance of insulating materials and heat-treated wood (Abdou and Budaiwi 2005; Srivaro *et al*. 2019; Olarescu *et al.* 2015, Pasztory *et al.* 2018). Their results demonstrated a linear relationship between mean temperature and increased thermal conductivity values. In addition, Berardi and Naldi (2017) noticed that the thermal response of materials treated to different temperatures significantly depends on the type of material. In materials with lower density, the variations become more clear.

In addition to operating temperatures, another important factor that has a big impact on the *k*-value of a material is its moisture content, which is affected by the humidity level of the surroundings. A material's *k*-value increases as its moisture content rises. This means that moisture diminishes the thermal performance of materials. The moisture content of materials used for walls and roofs is typically distinct in buildings. The amount of moisture in the insulating material is significantly influenced by the indoor environment, ambient air humidity, and moisture characteristics of the wall or roof system (Abdou and Budaiwi 2005).

The goal of this study was to evaluate the effect of changing operating temperature on the thermal conductivity variation of heat-treated wood depend on relative humidity and as a result, to estimate the relative sensitivity of *k*-value of heat-treated wood typically used in building constructions. Published *k*-values of heat-treated wood were evaluated at standard temperature and humidity conditions. However, depending on the prevailing climatic conditions, materials employed in building construction can be subjected to large changes in ambient temperature and relative humidity. Consequently, their real thermal behavior may be very different from the expected under standard conditions. Thus, a more realistic evaluation of the thermal insulation performance of heat-treated wood in different climates will result in a more accurate assessment of thermal performance and a more accurate estimate of energy-efficient design (Abdou and Budaiwi 2005).

EXPERIMENTAL

Materials

The samples with the dimensions of 25 mm × 100 mm × 100 mm (R, T, L) were prepared from the sapwood region of kiln-dried lumbers [made of one beech (*Fagus orientalis* L.) and one pine (*Pinus sylvestris* L.) stems from the region of Yenice Balıkısık and Bolu Mengen, Turkey respectively]. In this stage, samples that were reasonably straight-grained and free from any visual anomalies were chosen for the study to acquire the best results and optimize the variability in the data. In the beginning, there were a total of sixty flawless samples that were split into four groups, with each group having fifteen samples. The first group was used as a reference and did not undergo heat treatment. The remaining three groups were subjected to a heat treatment under nitrogen gas at the temperatures 180, 200, and 220 °C, respectively. Before the heat treatment, all samples (control samples included) were dried at 103 °C to reach constant weight to prevent the splitting of samples during heat treatment. Immediately after oven drying, reaching 0% equilibrium moisture content of wood, the samples were kept in a desiccator to prevent them from getting moisture until further processing. Prior to heat treatment, oven-dry samples were weighed, and the mass before heat treatment was determined.

Methods

Heat treatment

The heat treatment was performed in a vacuum oven with a sensitivity of ± 1 °C under nitrogen atmosphere. The whole process of heat treatment is made up of the following steps. Initially, the air inside the oven was vacuumed to reduce the ambient pressure to 100 to 150 mbar. The contact of the system with oxygen was prevented, and the ambient pressure was decreased to -900 mbar through a vacuum with a vacuum pump. The oven was filled with nitrogen gas until the pressure gauge again reached to 0 levels and set to target temperature (180, 200, and 220 °C). The temperature was increased by 1.5 °C min 1 from ambient (20 °C) to the target temperatures and maintained the target temperature for 2 h. Then the heating system was set to 103 ± 2 °C, and the temperature was decreased by 1 °C min 1 to 103 °C. When the oven temperature had cooled to 103 °C, the samples were removed from the oven and kept in a desiccator to prevent them from getting moisture during further cooling. Then the samples were re-weighed, and the post-heat masses were determined.

Climatization

After heat treatment, heat-treated pine (HTP) and heat-treated beech (HTB) samples were divided into three subgroups (each includes five test repetitions) to ascertain the thermal conductivity at various levels of relative humidity. The reason for choosing these climatization conditions is because they are similar to the usage areas of heat-treated wood, such as outdoor flooring, balcony flooring, and saunas. The relative humidity is 36% in indoor environments such as indoor flooring, 70% and 80% in outdoor flooring, balcony flooring, and roofing, and 80% in saunas. Prior to thermal conductivity measurement, the specimens were conditioned at 20 to 22 °C and 36, 70, and 80% relative humidity (RH) until a constant weight was reached. At the end of the climatization, the dimensions of wood samples and weights were measured sensitively, and the samples' density (δ) and equilibrium moisture content (ω) at different relative humidity were estimated according to Eqs. 1 and 2.

$$\delta = M / V \tag{1}$$

In Eq. 1, δ is the density (g/cm^3), M is the moist weight (g), and V is the moist volume (cm^3).

$$\omega = [(Mr - M_0)/M_0] \times 100 \tag{2}$$

In Eq. 2, ω is the moisture content (%), M_r is the moist weight (g), and M_0 is the oven dry weight (g).

Determination of thermal conductivity

The single-specimen guarded hot plate apparatus Taurus TLP 300 DTX meter (Taurus Instruments GmbH, Weimar, Germany) was used to measure thermal conductivity (*k*-value) in accordance with ISO 8302 (ISO standard 1991) (Fig. 1). The measurement is done in a circle with a 100 mm diameter in the middle of the sample, and the sample is typically 500 mm × 500 mm × sample thickness (L, T, and R). The outside sections provide protection against the effects of the environment. Standard conditions (500=500 mm^2) were simulated by placing samples with identical 100 mm x 100 mm x 25 mm (L, T, R) dimensions in the center of a plate and covering the plate's brims with wood plates of the same fiber orientation and thickness (Niemz *et al.* 2010; Sonderegger *et al.* 2011). Cold and hot plate temperatures were 5 °C/15 °C, 15 °C/25 °C, and 25 °C/35 °C. So, the *k*-value was recorded at temperatures 10, 20, and 30 °C. The change in temperature between the hot and cold plates was 10 °C. The total time it takes to measure each sample is 390 minutes, and the result was the average of 13 measurements.

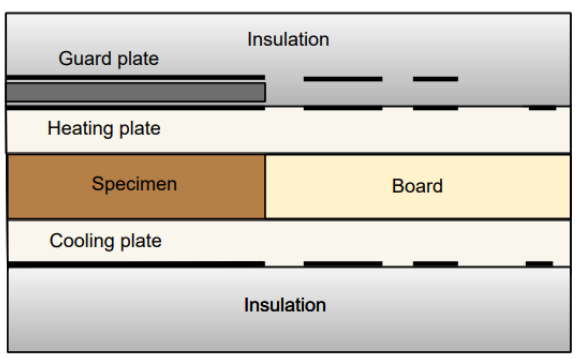

Fig. 1. Half-diagram of the single-specimen guarded heated plate apparatus

Fourier transform infrared (ATR-FTIR) analysis

After heat treatment, absorption spectra were analyzed to evaluate changes in the functional groups of wood cell wall components. Heat-treated and un-treated samples were ground and then measured. The spectra of each sample were obtained at a wavelength of 700 to 4000 cm^{-1} with a resolution of 4 cm^{-1}.

RESULTS AND DISCUSSION

Figures 2 and 3 show the *k*-values un- and heat-treated pine and beech samples as a function of relative humidity (RH) at 10, 20, and 30 °C mean plate temperatures.

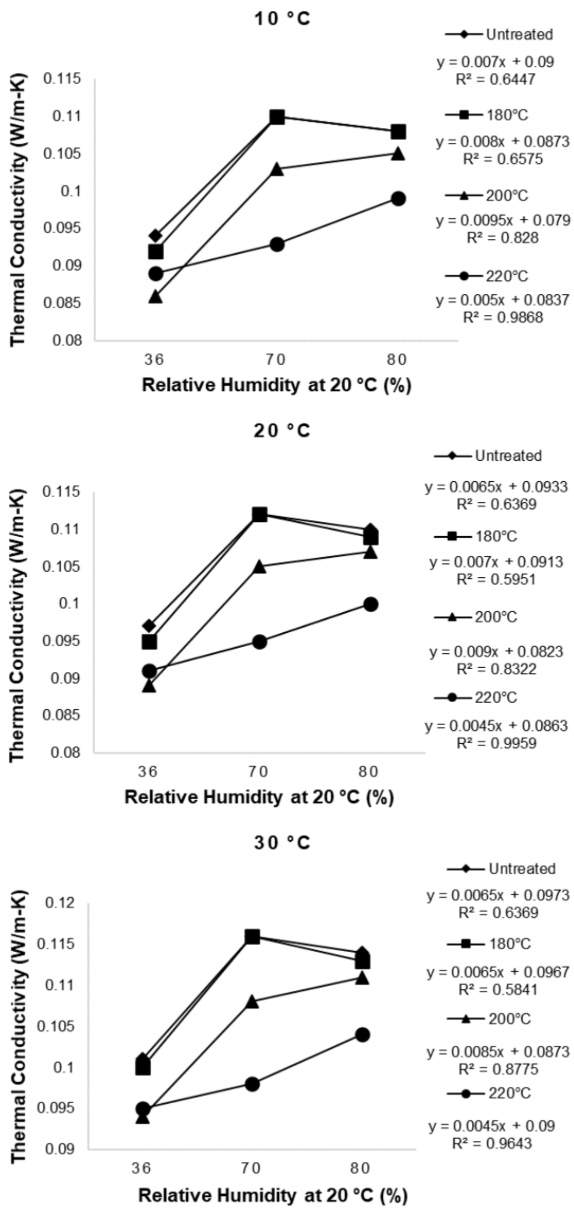

Fig. 2. Thermal conductivity of untreated and HTP specimens at mean plate temperatures of 10 °C, 20 °C, and 30 °C as a function of relative humidity

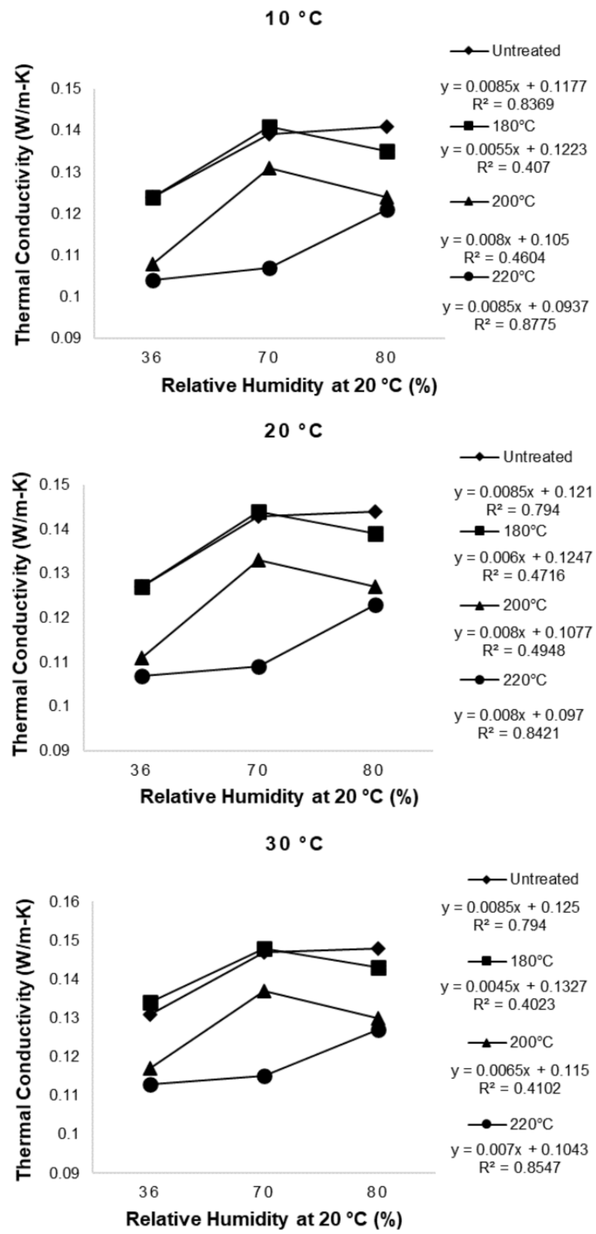

Fig. 3. Thermal conductivity of untreated and HTB specimens at mean plate temperatures of 10 °C, 20 °C, and 30 °C as a function of relative humidity

After applying heat treatment to pine (Fig. 2) and beech (Fig. 3), it was observed that their *k*-values decreased. The *k*-values of the samples decreased as the heat treatment temperature increased. A modest decrease in *k*-values was observed at 180 °C, but the variation quadrupled when the heat treatment temperature reached 220 °C.

There was a linear correlation between the *k*-value and RH in all samples, at the 95% confidence level. As RH increased, the *k*-value of samples linearly increased. The increasing trend of the *k*-value as a RH function appeared identical for untreated and 180 °C-heated samples. Considered with RH, the *k*-values of untreated and 180 °C heat-treated samples increased considerably from 36% to 70%. But the gap between 70% and 80% wasn't very big. The increase in *k*-value with increasing RH was more linear in samples treated to higher temperatures. The samples heat-treated at 220 °C had a much higher coefficient of determination (R^2 = 0.84 to 0.96) of the *k*-value with RH than the others. The first could say that there had been an improvement in the *k*-value's consistency with regard to the EMC of heat-treated wood when exposed to high temperatures.

Wood responds to changes in its moisture environment by absorbing and releasing water molecules. This happens when wood is exposed to environments with considerable variations in relative humidity (RH). EMC of wood results from the adsorption and desorption of water molecules over time in a steady environment of temperature and RH. Therefore, the potential of wood to adapt to its surroundings can be altered by modifying the EMC. Water absorption is always associated with an increase in thermal conductivity, since the thermal conductivity of water is approximately 20 times larger than that of stationary air. As a result, it is critical to investigate the effect of moisture on thermal performance, particularly in building insulating materials. According to the study's findings, heat treatment, reduced the EMC of wood (Table 1). As the heat treatment temperature was increased, the wood density somewhat decreased and the EMC decreased dramatically. As can be seen from the data in Table 1, the variation in EMC as a function of heat treatment temperature was significantly larger than the variation in density. It can therefore be concluded that the decrease in EMC may have a greater impact on the reduction in *k*-value caused by heat treatment. Pine and beech exhibited chemical alterations that impacted the physical qualities such as density and hygroscopicity during the heat treatment. As can be seen in Figs. 4 and 5, considerable variations were noticed, mostly around 220 °C. The decrease in wood porosity and MC was attributed to the deformation of cell wall components and changes in their chemical composition produced by a rise in heat treatment temperature.

Table 1. Moisture Content and Density Values of UT and HT Samples at Different Relative Humidity

		Pine		Beech	
Heat Treatment Temperature (°C)	**Relative Humidity at 20 °C (%)**	**Moisture Content (%)**	**Density (g/cm³)**	**Moisture Content (%)**	**Density (g/cm³)**
Untreated	36	7	0.597	7	0.648
	70	12.8	0.602	12.7	0.653
	80	16.2	0.605	16.1	0.662
180	36	4.1	0.522	3.7	0.638
	70	7.4	0.593	7.6	0.662
	80	10.4	0.588	10.9	0.66
200	36	3.8	0.552	3.4	0.623
	70	7.5	0.589	7	0.613
	80	10	0.574	10	0.65
220	36	3.6	0.563	3.3	0.622
	70	6.6	0.564	6.9	0.607
	80	8.7	0.56	8.5	0.593

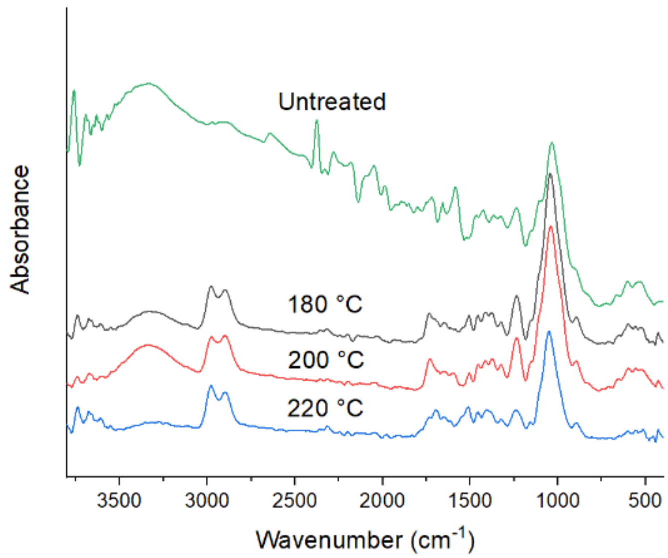

Fig. 4. FTIR spectra of untreated and heat-treated beech wood

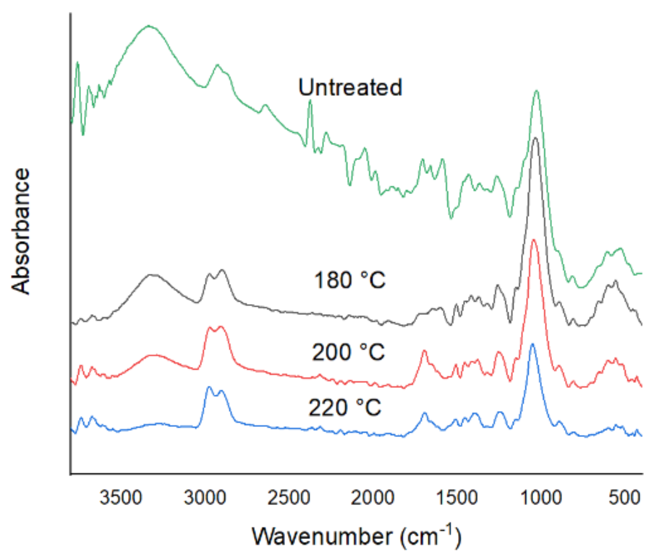

Fig. 5. FTIR spectra of untreated and heat-treated pine wood

It is known that the absorption bands of functional groups of wood are between 1800 and 800 cm^{-1}. These bands are caused by stretching and bending vibrations in the molecules, which give rise to absorbances in the so-called fingerprint zone. The bands between 3550 and 2900 cm^{-1} correspond to OH and C-H stretching. It is also significant for the primary components of wood (Kubovský *et al.* 2020). The band at 1030 cm^{-1} corresponds to C-O-C stretching of primary alcohols in cellulose and hemicelluloses (Esteves *et al.* 2013; Xing and Li 2014; Kubovský *et al.* 2020). It can be seen in Figs. 4 to 5 that this band declined with increasing heat treatment temperature. This shows that the hemicellulose and cellulose structure had slowly changed. At 2940 cm^{-1} (asymmetric CH_2 stretching) and 2880 cm^{-1} (symmetric CH_2 stretching) (Esteves *et al.* 2013; Xing and Li 2014; Kubovský *et al.* 2020), only minor alterations with a slight decrease in band intensities were observed. This verifies the thermal decomposition of lignin and alterations at the level of cellulose crystallinity. The band at 3335 cm^{-1} represents the OH stretching vibration in hemicelluloses and lignin (Esteves *et al.* 2013; Xing and Li 2014; Kubovský *et al.* 2020). In the analysis, there was a significant drop in this band. As shown in Figs. 5 and 6, the intensity of this peak decreased as the heat treatment temperature increased, and the wood became less hydrophilic (Huang *et al.* 2012).

It should be observed that for all RH settings, the *k*-values of HTP and HTB were lower than those of untreated ones. The heat treatment mainly affected the most hydrophilic compounds (Figs. 4 to 5). Depolymerization of carbohydrates, particularly hemicelluloses, results in a decrease in the overall number of hydroxyl groups. The hydroxyl groups have a direct impact on the absorption of water. Heat treatment can raise the relative percentage of crystalline cellulose, which is known for its low accessibility of hydroxyl groups to water molecules (Figs. 4 to 5) and can have a major impact on moisture absorption and polarity of wood. As a consequence, the treated wood has a lower water affinity (Herrera *et al.* 2014). This indicates that water uptake and absorption in wood slow down, so the amount of water in the wood decreases (Hill 2006; Gu and Hunt 2007; Sahin Kol 2009; Sahin Kol and Sefil 2011). The *k*-value of water is much higher than wood, so the *k*-value tends to increase as EMC increases or decreases as EMC decreases. The findings were consistent with prior research that had used heat treatment on other types of wood (Sahin Kol and Sefil 2011; Korkut *et al.* 2013; Sahin Kol and Aysal Keskin 2016; Pasztory *et al.* 2017, 2020; Pelit *et al.* 2017).

Heat treatment results in the depolymerization of some hemicellulose, cellulose and lignin molecules in the wood tissue, reducing the amount of wood material (Cheng *et al*. 2016). Thus, heat treatment reduces the number of solid substances within the wood, enlarges the pores, and increases the amount of through-pore porosity (Jang and Kang 2019; Jang *et al.* 2020; Čabalová *et al.* 2021; Mawardi *et al.* 2022). That is, heat-treated wood has a larger pore capacity and significantly more air content, resulting in a bigger effect of operating temperature on *k*-values. The *k*-value decreases with decreasing density (Sonderegger *et al*. 2011).

In addition, when the temperature of the heat treatment was increased, the *k*-values of HTP and HTB both fell, but at different rates, and the rate of decrease was greater in beech. At 80% relative humidity, the rate of change in unheated samples of HTP at 180, 200, and 220 °C was 0.6%, 2.7%, and 8.7%, while it was 3.7%, 12%, and 14% in HTB. Because the heat treatment temperature causes different chemical changes in softwood (pine) and hardwood (beech), the change rate of mass loss varies, and thus, the variation of pore size, and porosity, are different (Jang and Kang 2019). Previous studies have shown that hardwoods have less thermal stability than conifers (softwoods) because of differences in their chemical structures. Softwood and hardwood have different kinds and amounts of hemicellulose, and the xylans in hardwood are more likely to break down when heated than the mannans in softwood (Hill 2006; Sahin Kol and Sefil 2011; Pásztory *et al.* 2017).

Figures 6 and 7 display the influence of thermal conductivity on mean plate temperature for UT and HT samples under three distinct relative humidity conditions. All samples showed a linear relationship between the *k*-value and mean plate temperature at the 95% confidence level. For all heat treatment temperatures, the rate of change of *k*-value as a function of plate temperature was the same for HTP and HTB as it was for the untreated ones. The highest *k*-values were obtained in the samples where the average plate temperature was 30 °C, and the lowest *k*-values were obtained in the samples where the average plate temperature was 10 °C. A similar trend was also obtained in some studies in the literature (Olarescu *et al.* 2015; Pasztory *et al.* 2018; Srivaro *et al.* 2019). According to the findings of this investigation, the thermal conductivity of heat-treated wood increases linearly with temperature.

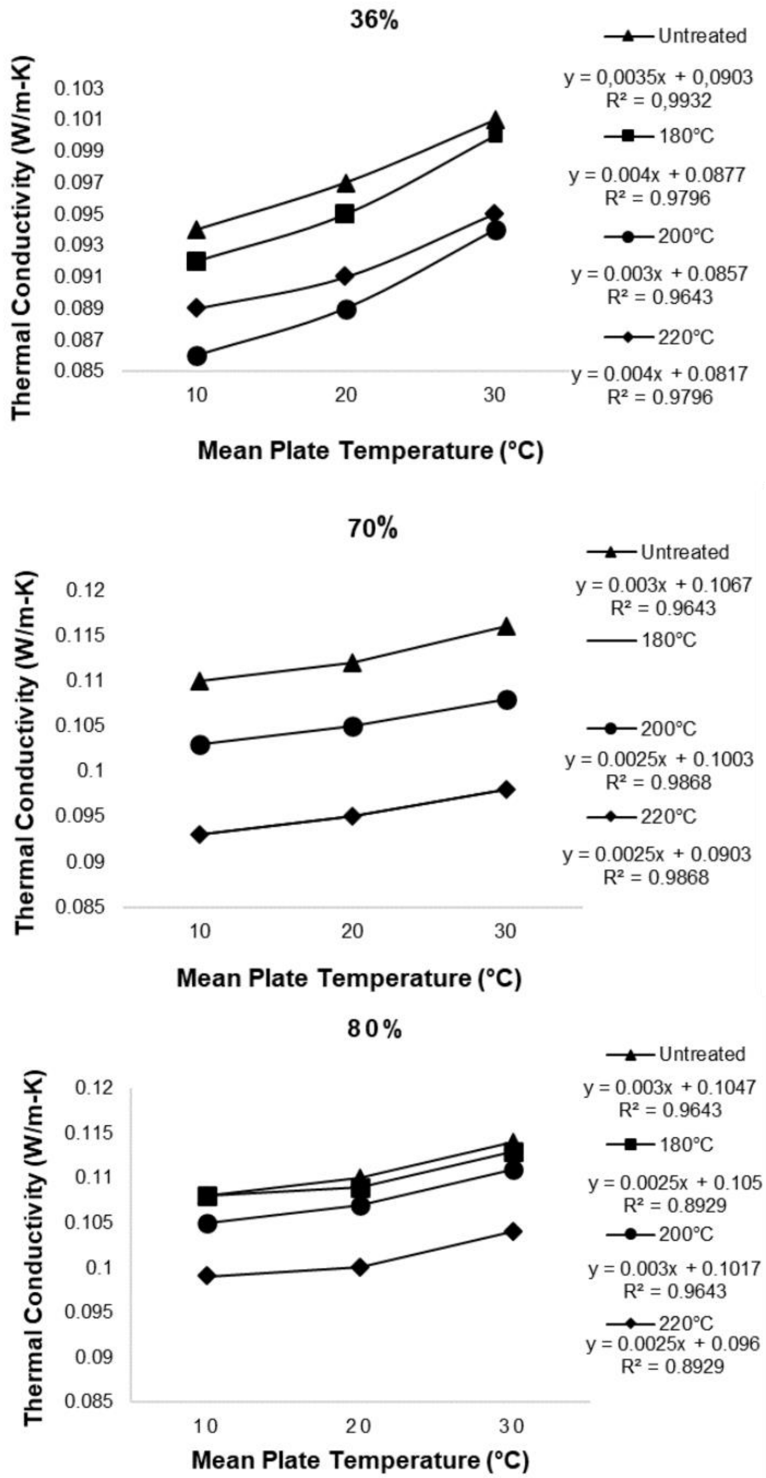

Fig. 6. Thermal conductivity of untreated and HTP specimens at three different moisture conditions of 36%, 70%, and 80% as a function of mean plate temperature

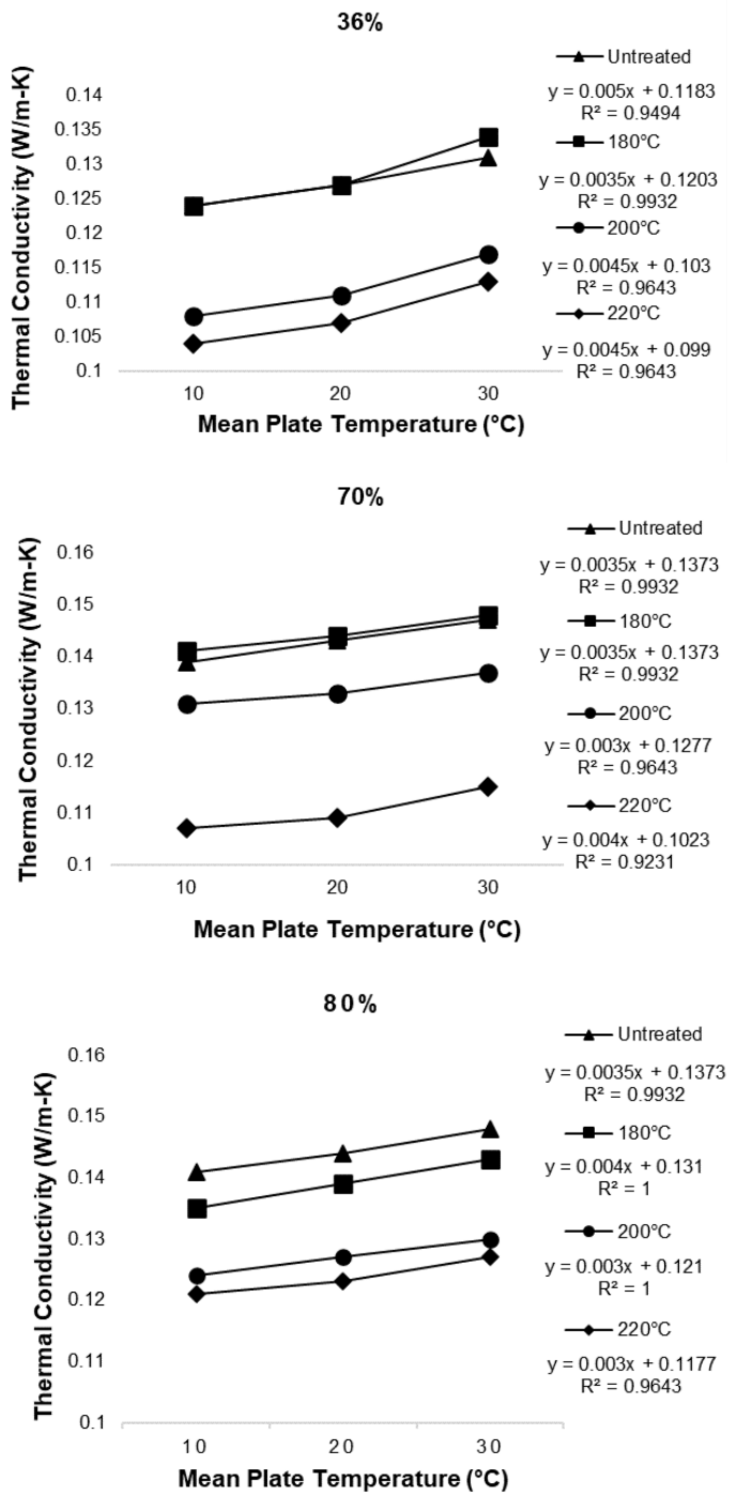

Fig. 7. Thermal conductivity of untreated and HTB specimens at three different moisture conditions of 36%, 70%, and 80% as a function of mean plate temperature

This research showed that higher-temperature-treated wood outperformed lower-temperature-treated wood in terms of thermal performance. The Wood Handbook states that for use as a thermal insulator for buildings, the *k*-value of material must be between

0.1 and 0.14 W/mK (Ross 2010). Even when subjected to the high levels of relative humidity (80%) and temperature difference (30 °C) seen in the study, *k*-value of HTP and HTB did not go above these ranges. Although HTP and HTB still were within this spectrum, where strength requirement is desired, low-temperature HTP is preferable. As a consequence of this, HTP and HTB can be employed as structural thermal insulation. When more insulation is needed, it was also shown that pine is superior to beech. Low-temperature heat-treated beech is preferable for applications where superior thermal insulation properties and satisfactory mechanical strength are required.

CONCLUSIONS

1. The thermal conductivity of heat-treated wood increased with the relative humidity. However, this difference was insignificant at small relative humidity changes. Accordingly, it can be said that the thermal conductivity of wood becomes more stable after heat treatment under relative humidity change. This indicates that heat treatment could improve the energy performance of wood subjected to prevailing climatic conditions.
2. Contrastingly, the thermal conductivity of heat-treated samples dependence on changes in temperature was similar to that of untreated specimens, showing a relatively high increase of thermal conductivity with an increase in the mean plate temperature. The thermal conductivity of wood was still sensitive to temperature after heat treatment, and the temperature dependence of the heat-treated wood was not affected by the relative humidity change.
3. Heat-treated pine exhibited a lower conductivity than heat-treated beech. According to heat treatment temperature, average plate temperature, and relative humidity, both variations were quite similar and can be considered insulating materials. However, pine can be preferred where higher insulation is desired.

ACKNOWLEDGMENTS

The authors declare that the material presented in this paper is the authors' original work, is not being considered for publication or has not been published elsewhere except for a M.Sc. thesis associated with a University degree. The authors acknowledge the funding support from the Karabük University, Department of Coordinator of Research Projects (Project number: KBÜBAP-16/1-YL-090).

REFERENCES CITED

Abdou, A. A., and Budaiwi, I. M. (2005). “Comparison of thermal conductivity measurements of building insulation materials under various operating temperatures,” *Journal of Building Physics* 29(2), 171-184. DOI: 10.1177/1744259105056291

Aydemir, D., and Gündüz, G. (2009). “The effect of heat treatment on physical, chemical, mechanical and biological properties of wood,” *Journal of Bartin Faculty of Forestry* 11(15), 71-81.

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

Berardi, U., and Naldi, M. (2017). “The impact of the temperature dependent thermal conductivity of insulating materials on the effective building envelope performance,” *Energy and Buildings* 144, 262-275. DOI: 10.1016/j.enbuild.2017.03.052

Budaiwi, I., and Abdou, A. (2013). “The impact of thermal conductivity change of moist fibrous insulation on energy performance of buildings under hot–humid conditions,” *Energy and Buildings* 60, 388-399. DOI: 10.1016/j.enbuild.2013.01.035.

Candelier, K., Thevenon, F. M., Petrissans, A., Dumarcay, S., Gerardin, P. and Petrissans, M. (2016).” Control of wood thermal treatment and its effects on decay resistance: A review,” *Annals of Forest Science* 73(3), 571-583. DOI: 10.1007/s13595-016-0541-x

Čabalová, I., Výbohová, E., Igaz, R., Kristak, L., Kačík, F., Antov, P., and Papadopoulos, A. N. (2022). “Effect of oxidizing thermal modification on the chemical properties and thermal conductivity of Norway spruce (*Picea abies* L.) wood,” *Wood Material Science & Engineering* 17(5), 366-375. DOI: 10.1080/17480272.2021.2014566

Cavus, V., Sahin, S., Esteves, B., and Ayata, U. (2019). “Determination of thermal conductivity properties in some wood species obtained from Turkey,” *BioResources* 14(3), 6709-6715. DOI: 10.15376/biores.14.3.6709-6715

Cheng, S., Huang, A., Wang, S., and Zhang, Q. (2016). “Effect of different heat treatment temperatures on the chemical composition and structure of Chinese fir wood,” *BioResources* 11(2), 4006-4016. DOI: 10.15376/biores.11.2.4006-4016

Coman, G., Uzuneanu, K., and Paraschiv, S. (2017). “The influence of moisture on thermal conductivity for building materials,” *Annals of the University Dunarea de Jos of Galati Fascicle IX. Metallurgy and Materials Science* 35(2), 29-33.

Czajkowski, Ł., Olek, W., and Weres, J. (2020). “Effects of heat treatment on thermal properties of European beech wood,” *European Journal of Wood and Wood Products* 78(3), 425-431. DOI: 10.1007/s00107-020-01525-w

Esteves, B., Velez, M. A., Domingos, I., and Pereira, H. (2007). “Influence of steam heating on the properties of pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) wood,” *Wood Science and Technology* 41(3), article 193. DOI: 10.1007/s00226-006-0099-0

Esteves, B. M., and Pereira, H. M. (2009). “Wood modification by heat treatment: A review,” *BioResources* 4(1), 370-404. DOI: 10.15376/biores.4.1.Esteves

Esteves, B., Velez Marques, A., Domingos, I., and Pereira, H. (2013). “Chemical changes of heat treated pine and eucalypt wood monitored by FTIR,” *Maderas. Ciencia y Tecnología*, *15*(2), 245-258. DOI: 10.4067/S0718-221X2013005000020

Fu, Z., Zhou, Y., Gao, X., Liu, H., and Zhou, F. (2019). “Changes of water related properties in radiata pine wood due to heat treatment,” *Construction and Building Materials* 227, article 116692. DOI: 10.1016/j.conbuildmat.2019.116692

Gu, H. M., and 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.

Gündüz, G., Niemz, P., and Aydemir, D. (2008). “Changes in specific gravity and equilibrium moisture content in heat-treated fir (*Abies nordmanniana* subsp. *bornmülleriana* Mattf.) wood,” *Drying Technology* 26(9), 1135-1139. DOI: 10.1080/07373930802266207.

Herrera, R., Erdocia, X., Llano-Ponte, R., and Labidi, J. (2014). “Characterization of hydrothermally treated wood in relation to changes on its chemical composition and physical properties,” *Journal of analytical and Applied Pyrolysis* 107, 256-266. DOI: 10.1016/j.jaap.2014.03.010

Herrera, R., Arrese, A., de Hoyos-Martinez, P. L., Labidi, J., and Llano-Ponte, R. (2018). “Evolution of thermally modified wood properties exposed to natural and artificial weathering and its potential as an element for façades systems,” *Construction and Building Materials* 172, 233-242. DOI:10.1016/j.conbuildmat.2018.03.157

Huang, X., Kocaefe, D., Kocaefe, Y., Boluk, Y., and Pichette, A. (2012). “Changes in wettability of heat-treated wood due to artificial weathering,” *Wood Science and Technology* 46, 1215-1237. DOI: 10.1007/s00226-012-0479-6

Hill, C. A. S. (2006). “Thermal modification of wood,” in: *Wood Modification*, John Wiley & Sons, Ltd., Chichester, England, pp. 99-126. DOI: 10.1002/0470021748.ch5

Jang, E. S., and Kang, C. W. (2019). “Changes in gas permeability and pore structure of wood under heat treating temperature conditions,” *Journal of Wood Science* 65(1), 1-9. DOI: 10.1186/s10086-019-1815-3

Jang, E. S., Yuk, J. H., and Kang, C. W. (2020). “An experimental study on change of gas permeability depending on pore structures in three species (hinoki, Douglas fir, and hemlock) of softwood,” *Journal of Wood Science* 66(1), 1-12. DOI: 10.1186/s10086-020-01925-9

Kamperidou, V. (2019). “The biological durability of thermally- and chemically-modified black pine and poplar wood against basidiomycetes and mold action,” *Forests* 10(12), 1111. DOI: 10.3390/f10121111

Kandem, D. P., Pizzi, A., and Jermannaud, A. (2002). “Durability of heat-treated wood,” *Holz als Roh-und Werkstoff* 60(1), 1-6. DOI: 10.1007/s00107-001-0261-1

Kocaefe, D., Poncsak, S., and Boluk, Y. (2008). “Effect of thermal treatment on the chemical composition and mechanical properties of birch and aspen,” *BioResources* 3(2), 517-537.

Korkut, S., Aytin, A., Tasdemir, C., and Gurau, L. (2013). “The transverse thermal conductivity coefficients of wild cherry wood heat-treated using the Thermowood method,” *ProLigno* 9(4), 679-683.

Kubovský, I., Kačíková, D., and Kačík, F. (2020). “Structural changes of oak wood main components caused by thermal modification,” *Polymers* 12(2), article 485. DOI: 10.3390/polym12020485

Mawardi, I., Aprilia, S., Faisal, M., and Rizal, S. (2022). “An investigation of thermal conductivity and sound absorption from binderless panels made of oil palm wood as bio-insulation materials,” *Results in Engineering* 13, article 100319. DOI: 10.1016/j.rineng.2021.100319

Nasir, V., Nourian, S., Avramidis, S., and Cool, J. (2018). "Prediction of physical and mechanical properties of thermally modified wood based on color change evaluated by means of "group method of data handling," *Holzforschung* 73(4), 381-392. DOI: 10.1515/hf-2018-0146

Niemz, P., Sonderegger, W., and Hering, S. (2010). "Thermal conductivity of Norway spruce and European beech in the anatomical directions," *Forestry and Wood Technology* 72, 66-72.

Olarescu, C. M., Campean, M., and Cosereanu, C. (2015). "Thermal conductivity of solid wood panels made from heat-treated spruce and lime wood strips," *ProLigno* 11(4), 377-382.

Pásztory, Z., Fehér, S., and Börcsök, Z. (2020). "The effect of heat treatment on thermal conductivity of paulownia wood," *European Journal of Wood and Wood Products* 78(1), 205-207. DOI: 10.1007/s00107-019-01470-3

Pásztory, Z., Horváth, N., and Börcsök, Z. (2017). "Effect of heat treatment duration on the thermal conductivity of spruce and poplar wood," *European Journal of Wood and Wood Products* 75(5), 843-845. DOI: 10.1007/s00107-017-1170-2

Pasztory, Z., Horvath, T., Glass, S., and Zelinka, S. (2018). "Experimental investigation of the influence of temperature on thermal conductivity of multilayer reflective thermal insulation," *Energy and Buildings* 174, 26-30. DOI: 10.1016/j.enbuild.2018.06.012

Pelit, H., Korkmaz, M., Budakçı, M., and Esen, R. (2017). "The effects of densification and heat treatment on thermal conductivity of fir wood," *The Online Journal of Science and Technology* 7(3), 117-122.

Priadi, T., and Hiziroglu, S. (2013). "Characterization of heat treated wood species," *Materials & Design* 49, 575-582. DOI: 10.1016/j.matdes.2012.12.067.

Ross, R. J. (2010). "Wood handbook: wood as an engineering material," *General Technical Report*, FPL-GTR-190. DOI: 10.2737/FPL-GTR-190

Rowell, R. M., Ibach, R. E., McSweeny, J., and Nilsson, T. (2009). "Understanding decay resistance, dimensional stability and strength changes in heat treated and acetylated wood," *Wood Material Science and Engineering* 4(1-2), 14-22. DOI: 10.1080/17480270903261339

Sonderegger, W., Hering, S., and Niemz, P. (2011). "Thermal behaviour of Norway spruce and European beech in and between the principal anatomical directions," *Holzforschung* 65(3), 369-375. DOI: 10.1515/hf.2011.036

Sahin Kol, H., and Aysal Keskin, S. (2016). "The thermal conductivity of solid wood heat-treated using the Thermowood method," in: *Proceedings of the International Conference on Material Science and Technology in Cappadoccia (IMSTEC'16)*, Nevsehir, Turkey, pp. 942-945.

Sahin Kol, H., and 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. DOI: 10.1002/app.33885

Sahin Kol, H. (2009). "Thermal and dielectric properties of pine wood in the transverse direction," BioResources 4(4), 1663-1669. DOI: 10.15376/biores.4.4.1663-1669

Sandberg, D., Haller, P., and Navi, P. (2013). "Thermo-hydro and thermohydro-mechanical wood processing: An opportunity for future environmentally friendly wood products," *Wood Material Science and Engineering* 8(1), 64–88. DOI: 10.1080/17480272.2012.751935

Sandberg, D., and Kutnar, A. (2016). “Thermal modified timber: recent developments in Europe and North America,” *Wood and Fiber Science* 48(1), 28-39.

Srivaro, S., Börcsök, Z., and Pásztory, Z. (2019). “Temperature dependence of thermal conductivity of heat-treated rubberwood,” *Wood Material Science & Engineering* 16(2), 81-84. DOI: 10.1080/17480272.2019.1608298

TS ISO 8302 (1991). “Thermal insulation determination of steady-state areal thermal resistance and related properties guarded hot plate apparatus,” Turkish Standard Institution, Ankara, Turkey

Xing, D., and Li, J. (2014). “Effects of heat treatment on thermal decomposition and combustion performance of *Larix* spp. wood,” *BioResources* 9(3), 4274-4287. DOI: 10.15376/biores.9.3.4274-4287

Yıldız, S., Gezer, E. D., and Yıldız, Ü. C. (2006). “Mechanical and chemical behavior of spruce wood modified by heat,” *Building & Environment* 41(12), 1762-1766. DOI: 10.1016/j.buildenv.2005.07.017

Article submitted: October 23, 2022; Peer review completed: November 29, 2023; Revised version received: June 6, 2023; Accepted: June 8, 2023; Published: June 21, 2023.

DOI: 10.15376/biores.18.3.5253-5268