Relationship Between the Thermal Conductivity and Mechanical Properties of Uludağ Fir and Black Poplar

Cemal Özcan [a] and Mustafa Korkmaz [b,]*

The relationship between the thermal conductivity and some mechanical properties of Uludağ fir and black poplar specimens were determined based on related standards. It was hypothesized that thermal conductivity can be used as a predictor for wood properties. The hot plate test method was used as a thermal conductivity testing method. The density, compression strength, modulus of rupture, and modulus of elasticity values were also measured. Pearson’s correlation coefficient was determined and both linear and multiple regression analyses were performed to estimate the relationship between the parameters. The correlation between the thermal conductivity and density values was strong, which was consistent with past findings. Also, there was a strong correlation between the thermal conductivity, modulus of rupture, and modulus of elasticity, while the compression strength and thermal conductivity had a moderate correlation. The regression equations and test graphs were also determined and shown. Overall, it can be claimed that the thermal conductivity could be used for predicting the density and mechanical properties of wooden materials.

Keywords: Thermal conductivity; Mechanical properties; Fir; Poplar; Non-destructive testing

Contact information: a: Department of Industrial Products Design, Karabuk University, Karabuk, Turkey; b: Department of Wood Products Industrial Engineering, Duzce University, Duzce, Turkey;
** Corresponding author: mustafakorkmaz@duzce.edu.tr*

INTRODUCTION

Wood, which has importance in the building and construction industry, is a bio-renewable and naturally obtained material. Also, it is anisotropic, chemically complex, viscoelastic, hygroscopic, fibrous, and the physical and chemical properties differ from one species to another. Because of its advanced mechanical strength properties and despite its low density, wood is the biggest rival of the new generation of building materials that have either already been developed or are being developed. Moreover, wooden materials are solid-flexible, have a long life, are easy to process, natural, provide a high level of thermal insulation, and have a low electrical conductivity. In this respect, concrete, plastic, and steel only have a few of these properties each (Kollmann and Côté Jr. 1968). As a whole, these properties explain why wood is still one of the most important natural resources. Despite all of the advantages, wood can be damaged by environmental factors, such as water (Brischke and Rapp 2008), different wavelengths of light (George *et al.* 2005), combustion (Budakçı *et al.* 2016), and fungi (Schultz *et al.* 2007), because of its organic structure. It can also be destroyed by arthropods (insects, crustaceans, *etc.*), which use wood for nutrients and shelter (Zabel and Morrell 2012; Reinprecht 2016). Almost all of these factors weaken the mechanical properties of the wood material, which limits its usage area and shortens its service life. These changes in the mechanical properties can lead to serious problems, especially when using wood as a building material. For this reason, it is essential to periodically test wooden materials, especially those that function as structural support elements.

Material testing techniques can be divided into two categories, depending on the effects on the material, which are destructive testing (DT) and non-destructive testing (NDT) (John 1992). The DT techniques change the physical structure of the material during testing and damage the mechanical properties. Therefore, it is often not possible to reuse the tested materials. Additionally, most DT tests need to be performed in a laboratory environment. Because of these disadvantages, NDT techniques have been developed as an alternative. Non-destructive testing refers to techniques that determine the chemical, physical, or mechanical features of a material without altering these properties and are used to determine if a material is appropriate for its intended use. Most of these techniques use some physical properties of the materials and aim to estimate properties not yet known (Fenner 1965; Prasad and Nair 2009). Although visual inspection, which is the most primitive and oldest assessment method, can be classified as an NDT technique, many NDT techniques make use of the acoustic and electrical properties of the material. Techniques such as X-ray imaging, magnetic resonance, thermal imaging, and micro-examination are also used in some cases (Brashaw *et al.* 2009).

Thermal conductivity (TC) refers to the capability of a material to transfer heat and can be expressed as the transfer of heat energy using different systems between the molecules of one or more objects that are directly or indirectly interacting with each other (Alwan 2011; Çengel and Ghajar 2015). These objects are thermodynamically balanced if there is no net transfer of heat or matter *via* conduction, convection, and/or radiation mechanisms, according to the zero-law of thermodynamics (Çengel and Ghajar 2015; Reisel 2016). Thermal conductivity (k or λ) can be described as the quantity of heat transferred through a unit thickness of a material per unit area per unit temperature difference. A lower TC value indicates that the material is a thermal insulator, and a higher TC value indicates the opposite (Tritt 2004).

The working principle of heat transfer *via* conduction is as follows. When matter is exposed to heat energy, the vibration energy of its atoms and molecules in the region exposed to the heat increases. These molecules and atoms collide with their neighbors and transfer some of their energy. This continues in a chain and only stops when the energy is no longer transferable (Tritt 2004; Alwan 2011; Reisel 2016). Thermal properties are good indicators for understanding the morphological properties of materials (Singha and Thakur 2008; Thakur *et al* 2011). Previous studies have reported strong relationships between thermal conductivity and density of different materials (Horai 1971; Chia 1985; Sturm *et al.* 1997; Uysal *et al.* 2004). Also, it is known that there is a strong positive correlation between density and mechanical properties (Evans and Ilic 2001; Downes *et al.* 2002; Hein *et al.* 2013; Osuji and Nwankwo 2017). In the light of these information, it can be argued that a relationship can be established between the mechanical properties and the thermal conductivity value of the wood material.

In recent years, the use of NDT techniques in determining the properties of wood has become increasingly imperative. These techniques, which are typically performed when the materials are being used, often do not require experience. Non-destructive testing techniques are based on the principle of determining the energy transmission or storage characteristics of a material. These characteristics are used as the indicator for the assessment process. The most commonly used energy sources include acoustics, electricity, vibration, and radiation (Brashaw *et al.* 2009). Although it is a type of energy, the number of studies on the use of heat as an energy source in non-destructive tests is relatively limited. There is a previous study that used TC as an indicator for mechanical properties (Dündar *et al.* 2012). However, the hot-wire TC testing method used in the cited study is debatable for measuring the heterogeneous and anisotropic materials, because the method relies on the supposition that hot-wire is covered with a homogeneous and isotropic material (Vozár 1996). Moreover, in the hot-wire method, the sample is regarded as an infinite material (Labudová and Vozárová 2002). As an alternative approach, it can be claimed that a hot-plate testing method, in which heat flows through one direction and the material is regarded as a finite element, can give more accurate and clear results. Moreover, since different types of wood have different mechanical properties, it is necessary to investigate the relationship between thermal conductivity and mechanical properties for different wood species in order to obtain a comparable database.

In this study, the relationship between the TC and mechanical properties was investigated by examining the behavior of heat using guarded hot plate (GHP) testing setup. Black poplar and Uludağ fir wood were used as the testing materials. First, the TC values of the samples were determined *via* the hot plate testing method. Then, various mechanical properties of the specimens were determined, including the modulus of rupture (MOR), modulus of elasticity (MOE), and compression strength (CS). Lastly, correlation and regression analyses were performed and interpreted to better understand the relationship between these values.

EXPERIMENTAL

Materials

Uludağ fir (*Abies nordmanniana*, subspecies *bornmulleriana*) and black poplar (*Populus nigra*) wood with a relatively low density were used for these experiments. The timber specimens used for the samples were obtained *via* random selection from timber markets in Karabük, Turkey. Fifty pieces of wood (with as few defects as possible, such as knots, rot, burl tissue, coarse grain, cracks, *etc.*) were cut from the sapwood to the dimensions 360 mm × 200 mm × 20 mm. A total of 100 samples from the two wood species were prepared. These specimens were kept in a climate cabinet at 20 °C ± 2 °C and a 65% ± 3% relative humidity until they reached a constant weight. The moisture content (MC) values of the specimens were recorded according to TS 2471 (2005). Special care was taken to ensure that the samples represented different density values and that these values were appropriate for a normal distribution. To keep the MC of the samples constant, the conditioned samples were kept in airless plastic bags until analysis.

Methods

Measurement of the thermal conductivity

The TC tests were conducted *via* a guarded hot plate test setup according to TS ISO 8302 (2002). The GHP test setup was designed using an Arduino development platform (Model Uno, Turin, Italy) by authors, and its calibration was controlled with reference plates. The device consisted of an electrically heated hot plate and a cold plate on the opposite surface. These plates were properly insulated to prevent heat loss. A test specimen was placed between these two flat plates and the hot plate was heated using an electric source. Using a DC power supply, a linear heat flow was created from the insulated hot plate (continuously and constantly supplied) to the cold plate (kept at a constant temperature). As the electric power supplied to the hot plate increased, the temperature of this plate increased. The heat flowed from the hot surface to the cold surface. When the system reached thermal equilibrium with a linear heat flow, the final temperature of the hot plate varied, depending on the thermal resistance of the material, electric power supplied to the hot plate, and temperature of the opposing surface. The TC value (k, W/mK) of a specimen was calculated using Eq. 1,

$$k = [(W / A) \text{ x } L] / \Delta T \tag{1}$$

where W is the power provided to the electrical resistance heater (W), A is the contact area of the resistance heater (m^2), ΔT is the temperature difference across the sample (K), and L is the sample thickness (m).

The tests were executed in the radial direction of the wood. When the system reached thermal equilibrium, the temperature data was collected *via* PT100 resistance temperature detectors (Model SRS, Reismann Sensortechnik GmbH, Rosengarten, Germany) on both surfaces and were recorded using PC software developed by authors. Then, this data was used to calculate the TC with Eq. 1.

Determination of density

After the TC tests, the samples were placed back in the conditioning cabinet (65% relative humidity at 20 °C). Then, the density values and mechanical properties of the samples were determined. The air-dry density values of the samples were calculated according to TS 2472 (1976). First, the dimensions of the samples were measured in three different directions (longitudinal, tangential, and radial) with a vernier caliper. Then, the sample volumes were calculated. Their weights were obtained with a precision scale (0.01 g). The density (δ) values of the samples were then calculated using Eq. 2,

$$\delta \text{ (g/cm}^3\text{)} = m / v \tag{2}$$

where m is the mass (g) and v is the volume of the sample (cm^3).

Mechanical tests

Mechanical tests were performed to determine the MOR, MOE, and CS of the samples. The MOR and MOE values of the samples were determined in accordance with TS 2474 (1976) and TS 2478 (1976), respectively. The MOR and MOE were calculated *via* Eqs. 3 and 4, respectively,

$$MOE \text{ (GPa)} = PL^3 / 4bh^3 f \tag{3}$$

$$MOR \text{ (MPa)} = (3P_{\max} L / 2bh^2) \tag{4}$$

where P is the difference between the mean of the lower and upper limits of the force (N), b and h are the width and height of the sample (mm), respectively, f is the displacement at the point of fracture (mm), L is the span between the bearings (mm), and $P_{\max}$ is the fracture force (N).

The CS tests were conducted according to ISO 13061-17 (2017) and the CS was calculated *via* Eq. 5,

$$CS \text{ (MPa)} = P_{\max} / bh \tag{5}$$

where $P_{\max}$ is the maximum force (N) applied to the specimen, and b and h are the width and height of the sample (mm), respectively.

After the mechanical tests, the MC of the specimens was calculated in accordance with TS 2471 (2005). The test results of the samples with a MC that was different from the air-dried MC (12%) were recalculated *via* Eq. 6,

$$\sigma_{12} = \sigma_{\mathrm{m}} [1 + \alpha (m_2 - 12)] \quad (6)$$

where σ_{12} is the force value at a 12% moisture ratio (MPa or GPa), σ_{m} is the strength at a different MC (MPa or GPa), and m_2 is the MC of the sample during testing (%). The α is a correction coefficient value specified in the relevant standard for each test ($\alpha_{\mathrm{MOE}} = 0.02$, $\alpha_{\mathrm{MOR}} = 0.04$, and $\alpha_{\mathrm{CS}} = 0.05$).

RESULTS AND DISCUSSION

A descriptive statistical analysis was performed on all of the data. For each test, the mean, standard deviation (Std. Dev.), coefficient of variation (CV), minimum (min.), and maximum (max.) values were determined and are given in Table 1.

Table 1. Results of the Descriptive Statistical Analysis

Wood Type	Statistic Type	Moisture (%)	Density (g/cm^3)	TC (W/mK)	MOR (MPa)	MOE (GPa)	CS (MPa)
Black Poplar	Mean	12.13	0.488	0.114	85.498	11.05	45.822
	Std. Dev.	0.212	0.017	0.001	1.655	0.189	1.532
	CV (%)	1.77	3.58	1.59	1.94	1.71	3.34
	Min.	11.5	0.46	0.111	82.41	10.66	42.62
	Max.	12.7	0.519	0.117	87.93	12.34	48.67
Uludağ Fir	Mean	11.84	0.402	0.108	68.447	10.698	46.272
	Std. Dev.	0.175	0.017	0.003	2.866	2.057	3.754
	CV (%)	1.46	4.25	3.63	4.19	3.69	8.11
	Min.	11.4	0.372	0.101	62.78	9.74	39.37
	Max.	12.5	0.433	0.115	73.64	12.1	53.71

According to Table 1, the average density of the black poplar samples was 21% higher than that of the fir samples. Additionally, the average TC (5.5%), MOR (24%), and MOE (3%) values for the poplar samples were higher than that of the fir samples. Conversely, the difference between the average CS values of the samples was less than 1%. Before performing the correlation tests, the results were tested to determine whether the samples had a normal distribution. Kolmogorov-Smirnov (KS) normality tests were performed to evaluate the data distribution for each test. According to the KS normality test results, the data obtained from all of the experiments was normally distributed ($p < 0.05$), except for the MOE of the black poplar wood. The correlations were analyzed in accordance with the guide suggested by Evans (1996). According to this guide, 0 to 0.29 is a very weak correlation, 0.30 to 0.49 is a weak correlation, 0.50 to 0.69 is a moderate correlation, 0.70 to 0.89 is a strong correlation, and 0.90 to 1.0 is a very strong correlation. A Pearson or Spearman correlation analysis (R_{p} and R_{s}, respectively) was performed depending on whether the data was normally distributed or not, respectively. Then, a simple linear regression test was applied to detect any relationships between the parameters; the results are given in Table 2. The regression scatterplots are given in Figs. 1 and 2.

Table 2. Correlation and Linear Regression Test Values

Wood Type	Independent Variable	Dependent Variable	R^2	Sig.	R_p	R_s	Sig.
Black Poplar	TC	Density	0.84	< 0.05	0.91	-	< 0.05
		MOR	0.83	< 0.05	0.91	-	< 0.05
		MOE	0.66	< 0.05	-	0.77	< 0.05
		CS	0.64	< 0.05	0.79	-	< 0.05
	Density	MOR	0.86	< 0.05	0.92	-	< 0.05
		MOE	0.72	< 0.05	-	0.85	< 0.05
		CS	0.79	< 0.05	0.87	-	< 0.05
Uludağ Fir	TC	Density	0.89	< 0.05	0.94	-	< 0.05
		MOR	0.77	< 0.05	0.88	-	< 0.05
		MOE	0.74	< 0.05	0.86	-	< 0.05
		CS	0.76	< 0.05	0.87	-	< 0.05
	Density	MOR	0.84	< 0.05	0.91	-	< 0.05
		MOE	0.74	< 0.05	0.86	-	< 0.05
		CS	0.77	< 0.05	0.88	-	< 0.05

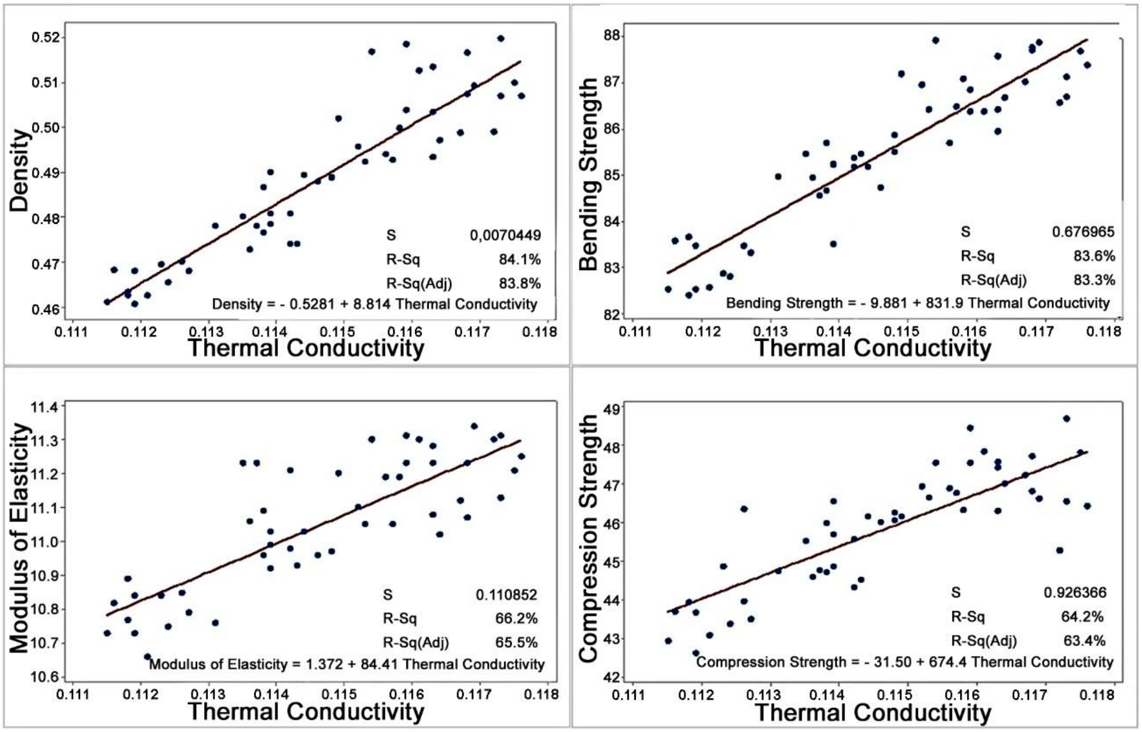

Fig. 1. Linear regression scatterplots of the black poplar samples

When the results were statistically analyzed, similar positive correlations were found for all of the pairs. Especially, the correlation between the TC and density was found to be strong for both types of wood. It has been reported in previous studies that the density of wood substance without voids ranges from 1.49 to 1.52 g/cm^3 regardless of the wood species (Kellogg and Wangaard 1969). In the porous materials, differences between the thermal conductivity of species arise due to differences in their porosity (Short and Kinniburg 1978). This is why, although fir and poplar species have different density and TC values, the correlation of these values was similar.

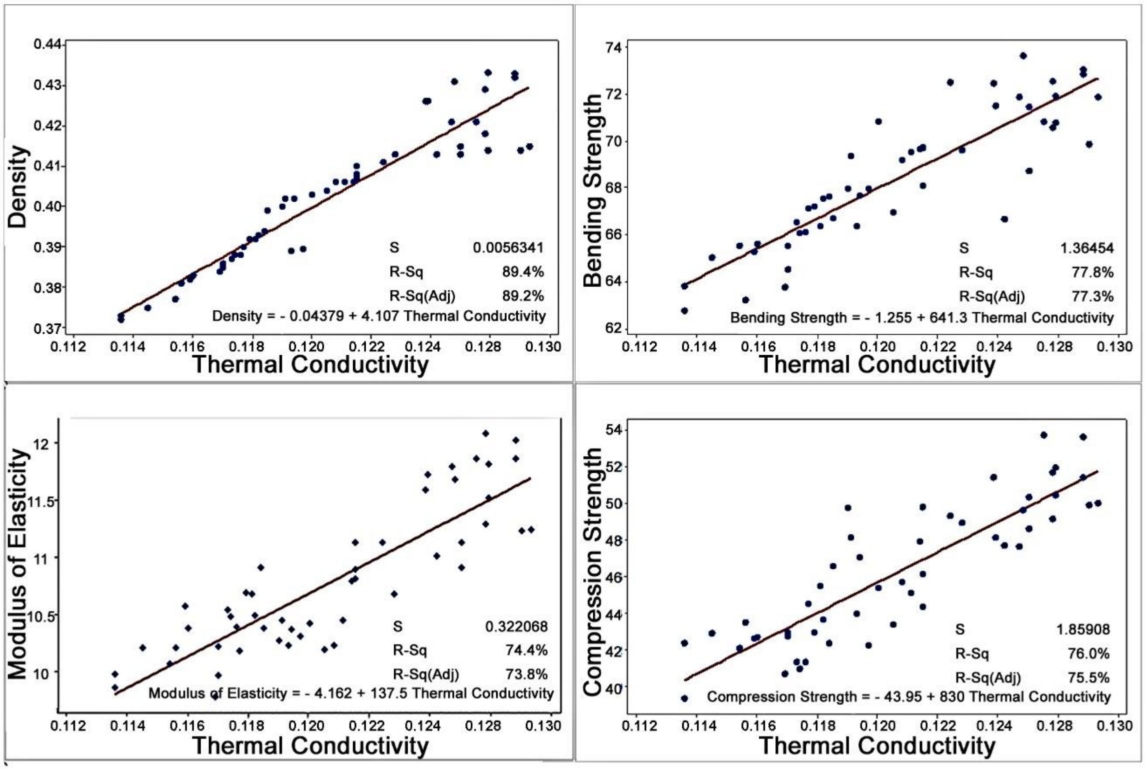

Fig. 2. Linear regression scatterplots of the Uludağ fir samples

Previous studies have also stated that there was a considerable relationship between density and TC (Sturm *et al.* 1997; Suleiman *et al.* 1999; Uysal *et al.* 2004). Similar to this study, Dündar *et al.* (2012) reported strong relationships between the TC and the MOR and MOE values of beech, fir, and pine species. However, the relationship between CS and TC was reported to be unimportant ($R^2 \leq 0.2$). In this study, a moderate-strong relationship was found between these two values ($R^2_{UF} = 0.64$ and $R^2_{BP} = 0.74$) according to linear regression test results. It is thought that this difference is because of the difference in the method used for the TC measurement.

Additionally, the MOR, MOE, and CS had a high correlation with the density. A previous study declared that there were strong relationships between the density and both the MOE ($R^2 = 0.81$) and MOR ($R^2 = 0.80$) (Yang and Evans 2003). There were also studies that have shown how the density can positively affect some mechanical properties of wood (Evans and Ilic 2001; Downes *et al.* 2002; Hein *et al.* 2013; Osuji and Nwankwo 2017).

The relationship between the TC and all of the mechanical tests was similarly positive and strong. When the regression values of the black poplar specimens were examined, it was found that the TC was a significant predictor of the MOR ($R^2 = 0.83$). However, the TC only had a moderate explanatory power for both the MOE (66%) and CS (64%). The regression model for the mechanical tests using the TC for Uludağ fir wood had a strong explanatory power. The results of these regressions were as high as the density regression. Overall, moderate and strong regressions were detected between the TC and both the MOE and CS in both wood types.

Multiple regression tests were applied to this data to establish a stronger regression relationship using the density and TC data as independent variables, and the results are shown in Table 3 and Fig. 3.

Table 3. Multiple Regression Test Results

Wood Type	Independent Variables	Dependent Variable	R²	Sig.
Black Poplar	TC - Density	MOR	0.87	< 0.05
		MOE	0.73	< 0.05
		CS	0.79	< 0.05
Uludağ Fir	TC - Density	MOR	0.84	< 0.05
		MOE	0.77	< 0.05
		CS	0.79	< 0.05

The multiple regression equations of samples are as follows:

$$MOR_{BP} = 15.12 + 47.9\ Density + 410\ TC \tag{7}$$

$$MOE_{BP} = 5.14 + 7.22\ Density + 20.8\ TC \tag{8}$$

$$CS_{BP} = 13.07 + 85.4\ Density - 78\ TC \tag{9}$$

$$MOR_{UF} = 4.41 + 129.3\ Density + 110\ TC \tag{10}$$

$$MOE_{UF} = -3.27 + 20.44\ Density + 53.5\ TC \tag{11}$$

$$CS_{UF} = -38.70 + 119.8\ Density + 338\ TC \tag{12}$$

When both independent variables were introduced into the regression model, better results were obtained than *via* a simple linear regression.

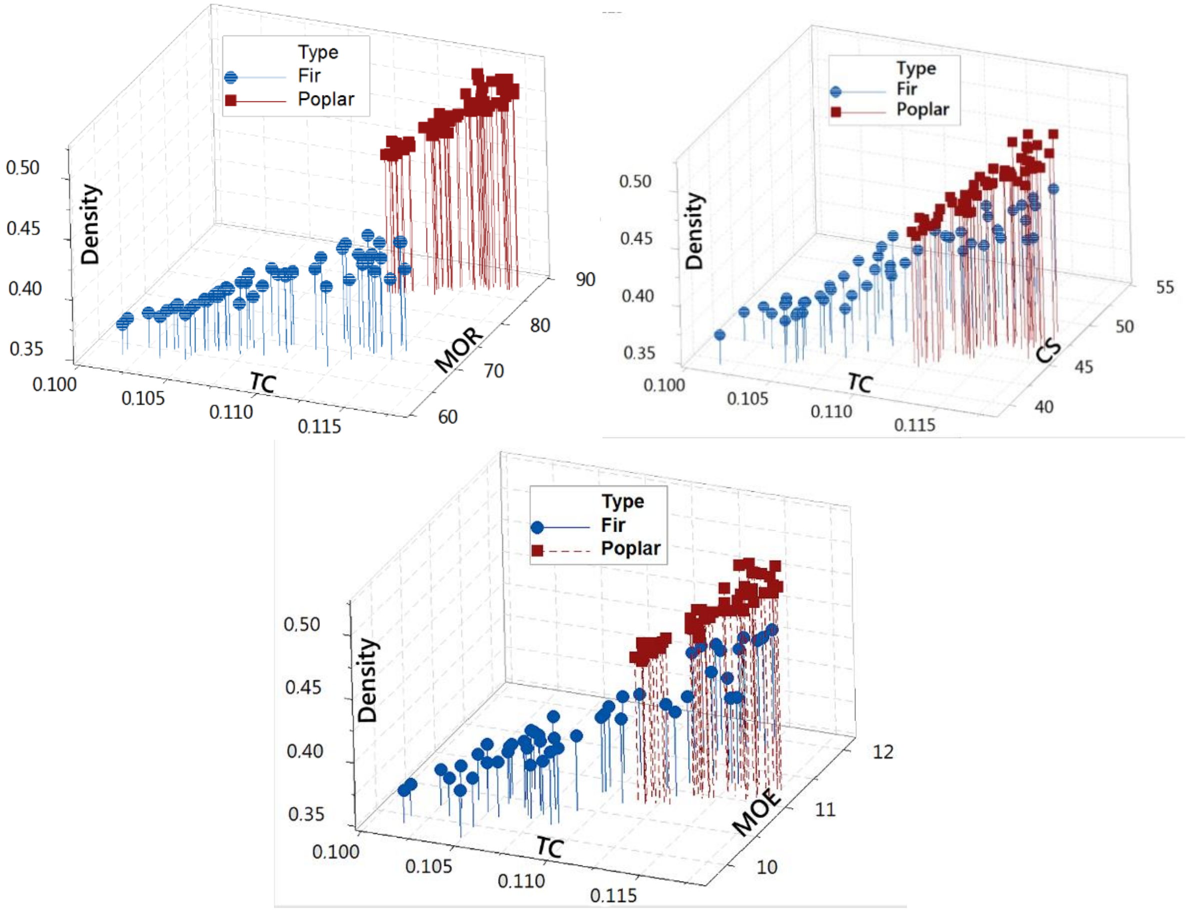

Fig. 3. Multiple regression matrices of the samples

With the multiple regression model, the explanatory power of MOR (regression value) of the black poplar wood increased by 4% compared with the simple linear regression TC value. This ratio was found to be 7% for the MOE and 15% for the CS. Similarly, the regression values for Uludağ fir wood increased by 7% for the MOR and by 3% for both the MOE and CS. The explanatory power of the multiple regression model, notably for CS of black poplar, is remarkably increased compared to the linear regression. Thus, a stronger regression model was established than the linear regression.

It can be argued that the mechanical properties of the test samples, with known density and TC values, can be estimated with a high accuracy. However, because the measurements were obtained from flawless samples, future testing should focus on whether wood defects affect the mechanical properties. Moreover, performing the tests at a 12% MC and with specimens that met the mechanical standards did not simulate service conditions. In particular, the effect of the moisture content on the TC was quite high and it was almost impossible to keep it constant during testing. These factors, originating from the fibrous and organic structure of the wood material, have similar negative effects on many DT and NDT techniques. Although the effects of these factors in determining the TC are partly known, there are no studies where all of the variables are taken into consideration. From this perspective, the effects of these variables on the TC are an important study topic and will be examined in future studies. In particular, more detailed and comprehensive investigations are needed to determine the effects of other parameters, such as wood defects and grain angle. Moreover, the availability of tools, such as machine learning, can be tested to establish new and more robust prediction models. Also, more accurate results can be achieved by establishing prediction models at different humidity levels. The association of real-time moisture measurements with the test results can make the test results more reliable.

CONCLUSIONS

1. Thermal conductivity tests were evaluated as an alternative non-destructive testing (NDT) method, and it was found that these tests can be useful in defining the mechanical properties of wood materials.
2. By testing the relationship between the density and thermal conductivity (TC), which constituted the theory of this work, a positive and strong correlation, as well as a regression model between these two values, was revealed.
3. For more accurate estimation of the mechanical test values, the multiple regression model was derived using the density and TC data as independent variables. This model has higher explanatory power than simple linear regression model for both wood types.
4. The relationships between the tested mechanical properties and TC were also revealed. The results obtained in this study showed that the TC can be used to estimate the mechanical properties of a wood material.

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