Kastamonu Uni., Orman Fakültesi Dergisi, 2022, 22(1): 33-39 Research Article
Kastamonu Univ., Journal of Forestry Faculty
Doi:10.17475/kastorman.1095741

Effects of Moisture and Direction of Grain on the Thermal Conductivity and Mechanical Properties of Black Alder and Scots Pine

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Received Date: 10.12.2020 Accepted Date: 13.12.2021

Abstract

Aim of study: Relationships between moisture content and thermal conductivity and mechanical properties of wood species were examined.

Material and methods: Black Alder *(Alnus glutinosa* L.) and Scots Pine (*Pinus sylvestris* L.) specimens were used. Thermal conductivity, modulus of rupture, compression strength and impact bending strength values were determined and analyzed. All specimens were examined at 3 different moisture levels which are oven-dry, fiber saturation point (FSP) and completely wet.

Main results: The lowest thermal conductivity value was found in the perpendicular to the grain direction of oven dried Black Alder samples as 0.119 W/mK. The highest thermal conductivity value was found in the parallel direction of Scots pine samples with FSP humidity content as 0.340 W/mK. In addition, the thermal conductivity value parallel to the grain is significantly higher than perpendicular one at all three moisture levels.

Highlights: While there is a positive linear relationship between the moisture content of the wood and its dynamic bending resistance and thermal conductivity; It was found that there is a negative linear relationship between bending strength and compressive strength value.

Keywords: Thermal Conductivity, Moisture Content, Grain Direction, Impact Bending Strength

Kızılağaç ve Sarıçam Odununun Isıl İletkenliği ve Mekanik Özellikleri Üzerine Rutubet Miktarı ve Lif Yönünün Etkileri

Öz

Çalışmanın amacı: Çalışmada, ağaç malzemenin sahip olduğu nem içeriği ile ısıl iletkenliği ve mekanik özellikleri arasındaki ilişkiler incelenmiştir.

Malzeme ve yöntem: Testlerde kızılağaç (*Alnus Glutinosa* L.) ve sarıçam (*Pinus Syl*vestris L.) odunlarından elde edilen örnekler kullanılmıştır. Isıl iletkenlik, eğilme direnci, basınç direnci ve dinamik eğilme (şok) direnci değerleri belirlenmiş ve analiz edilmiştir. Tüm numuneler tam kuru, lif doygunluğu noktası ve tamamen yaş olmak üzere 3 farklı nem seviyesinde incelenmiştir.

Temel bulgular: En düşük ısıl iletkenlik değeri, 0.119 W/mK ile tam kuru haldeki kızılağaç örneklerin örneklerinin liflere dik olarak yapılan ölçümlerinden elde edilmiştir. En yüksek ısıl iletkenlik değeri ise, 0.340 W/mK ile lif doygunluğu rutubetine sahip sarıçam örneklerinde liflere paralel yönde bulunmuştur. Ayrıca, liflere paralel ısıl iletkenlik değeri, her üç nem seviyesinde de dik olandan önemli ölçüde daha yüksek bulunmuştur.

Araştırma vurguları: Ağaç malzemenin nem içeriği ile dinamik eğilme direnci ve ısıl iletkenliği arasında pozitif doğrusal; eğilme direnci ve basınç direnci değeri arasında ise negatif doğrusal bir ilişki olduğu bulunmuştur.

Keywords: Isı İletkenliği, Nem Miktarı, Lif Yönü, Çarpmada Eğilme Dayanımı

Introduction

Wood has been used by mankind for building and tool making for at least as long as recorded history. It is a natural, sustainable, and long-lasting material and each type of wood shows different mechanical and physical properties (Kollmann and Cote, 1968; Kurt et al., 2008; Tsoumis, 1968). This is also true for specimens of the same species grown under

Citation (Atıf): Kurt, S., & Korkmaz, M. (2022). Effects of Moisture and Direction of Grain on the Thermal Conductivity and Mechanical Properties of Black Alder and Scots Pine. *Kastamonu University Journal of Forestry Faculty*, 22 (1), 33-39.

different conditions. The effects of these differences on the properties of wood are an important topic.

Heat is an energy and transmitted by conduction in solids like wood, substantially. The wood molecules in contact with each other transfer heat between them (Kreith and Black, 1980). Thermal conductivity (TC) can be defined as the rate at which heat is transferred by conduction through a unit cross-section area of a material when a temperature gradient exits perpendicular to the area. It is a characteristic feature of a material and it is generally measured in W/mK (Cengel and Ghajar, 2010).

Compared to other building materials, the TC of wood material is relatively low because of its porous structure. The main reason for the increase of the TC of the wood material with increasing humidity is that the water has a seriously higher TC than wood. Dry wood is one of the best thermal insulation materials because the cell wall has low conductivity and the voids of dry cells completely filled with air, an excellent insulator, instead of water (Desch and Dinwoodie, 1996). Besides moisture content, thermal conductivity of wood depends on some other factors such as amounts of extractives, fiber direction, structural defects, porosity, angle of fibrils, and density. There is a positive relationship between the density, amount of moisture and extractive content of wood and its TC. (Kollmann and Cote, 1968; Simpson and TenWolde, 1999; Taoukil et al., 2013; Kabakçi and Kesik 2020).

Dündar et al. (2012) found positive correlations between the TC of some wood materials and their mechanical properties. Özcan and Korkmaz (2018) reported that there is positive relation between thermal and mechanical properties of air-dried poplar and fir samples in radial direction.

Although many mechanical properties of wood material change depending on moisture, its resistance to dynamic loads does not change. In fact, as with static loads, resistance to dynamic loads decreases with increasing moisture. On the other hand, since the increase in moisture increases the flexibility of the wood material, no significant change in the resistance to dynamic loads can be observed depending on the moisture (Skaar, 1984; Winandy and Rowell, 1984).

Various studies on the mechanical properties of wood have shown that the mechanical properties of different wood species are different, and the fiber direction significantly changes the mechanical properties. The longitude direction has greater mechanical properties than transverse direction (Roszyk et al., 2020; Zhong et al., 2011). In different directions, the yield mechanism of wood differs. In particular, in the longitude direction, the yield mechanism of wood is mostly dependent on the yield and fold of the wood fiber itself, whereas in the transverse direction, the principal reason is slippage damage between wood fibers. Previous research has also revealed that the mechanical properties of a transverse surface vary depending on whether it is examined in the radial or tangential directions (Fu et al., 2021; Li et al., 2018; Y. Aydın and Ozveren, 2019; Yang and Zhang, 2018).

It is hoped that this study will contribute to an in-depth understanding of the effect of moisture and fiber direction on mechanical properties and thermal conductivity of wood.

Material and Method

Wood Material

Black Alder (*Alnus Glutinosa* L.) and Scots Pine (*Pinus Sylvestris* L.) woods were supplied randomly from timber merchants of Karabük, Turkey. Flawless (with as few defects as possible, such as knots, rot, burl tissue, coarse grain, cracks, etc.) specimens were used in both species with a dimension of 20 mm (thickness) x 20 mm (width) x 320 mm (length) for impact bending strength and modulus of rupture tests; 20 mm (T) x 20 mm (W) x 30 mm (L), and 20 (T) x 20 (W) x 25 (L) mm for moisture content measurements.

All moisture content values of the specimens were recorded according to TS 2471 (TS 2471, 1976). The fiber saturation point (FSP) of samples were calculated by determining the ratio of the total volumetric shrinkage to basic density. Samples were soaked in water and their fully wet volumes were determined when they reached constant weight. Then, samples were kept in oven at 103 °C ± 2 °C until they reached constant weight. The basic density of samples was calculated dividing their oven-dry mass by their green volume. Last, the FSP of samples was calculated by using the following equation:

$$FSP=VS/Db\ (\%) \qquad (1)$$

where Db is basic density and VS is the volumetric shrinkage (%).

The specimens were put in a climate cabinet at a temperature of 20 °C ± 2 °C and 65% ± 3% relative humidity and weighed (0.01 g precision) at daily intervals until they reached constant weight to obtain air-dried samples. Also, samples were dried in an oven at 103 °C ± 2 °C until obtaining a constant weight to obtain samples have moisture content at 0 % (oven dried). To keep moisture content values of the sample's constant, the conditioned samples were packet in plastic bags until testing.

Thermal Conductivity Measurements

ASTM C 1113-99 hot-wire method was used. TC coefficient values of samples were obtained by using a thermal conductivity testing device (QTM Quick Thermal Conductivity Meter - 500) which was based on non-steady state hot-wire method. The probe, consisting of a heating wire and a thermocouple, is supplied with constant electrical power (energy), and the measurement is made depending on the temperature of the wire at a certain time. Accordingly, when the wire is supplied with equal power in a specified time, it is expected that the temperature of the wire will be higher in the samples with less TC and less in the samples with higher TC. In the hot wire method, the sample sizes have no direct effect on the test results. However, samples should be thick and wide enough to prevent heat escape from the edges during measurement (KEM, 2020).

Density and Mechanical Strength Properties

After TC measurements, the density values of the specimens were obtained according to TS 2472 (1976). Then, the impact bending strength (TS 2477, 1976), the modulus of rupture (TS 2474, 1976), and the compression strength tests (ISO 13061-17, 2017) were applied to samples to evaluate mechanical properties.

Impact bending strength (IBS) was determined on a pendulum impact machine. The samples were positioned the hammer would act in the radial direction. The test was carried out with a constant span between the support centers of 240 ± 1 mm. The strength value was calculated via Eq. 2:

$$IBS\ (J/cm^2) = Q/bh \qquad (2)$$

where IBS is impact bending (J/cm^2), Q is the work needed for breaking the sample (J), a is the width of sample (cm), and b is the thickness (cm).

The modulus of rupture (MOR) and compression strength (CS) test were were measured using a Universal testing machine. The MOR values of the samples were calculated via Eq. 3:

$$MOR\ (N/mm^2) = (3P_{max}\ L/2bh^2) \qquad (3)$$

where, b and h are the width and height of the sample (mm), respectively, L is the span between the bearings (mm), and P_{max} is the fracture force (N).

The CS values were calculated via Eq. 4:

$$CS\ (N/mm^2) = P_{max}\ /\ bh \qquad (4)$$

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.

All data analyzed and interpreted to better understand the effects of moisture and grain direction on the TC and mechanical properties. Analysis of variance (ANOVA) followed by a Duncan test was used to identify the differences among various groups.

Result and Discussion

The average density values of the samples with three different moisture contents is given in the Table 1.

Table 1. Density values of samples

Wood Type	Oven dry density(g/cm^3)	Air dry density(g/cm^3)	Density at FSP (g/cm^3)
Black Alder	0.520	0.580	0.660
Scots Pine	0.489	0.545	0.706

According to Table 1, the highest average density values were found in samples with moisture content at FSP. Since the density of wood is lower than that of water, it is expected that the density of wood will increase as the amount of water per unit volume increases. TC and some mechanical properties of Scots pine and black alder woods were tested. The values are given Table 2.

In both wood types, TC value increased in parallel with the increase in moisture. In addition, TC value in parallel to the grain (//) were found higher than perpendicular to the grain (⊥). The minimum TC value of black alder was 0.119 W/mK in the perpendicular to grain (⊥) direction of the oven-dried samples. In addition, the maximum was 0.305 W/mK in the parallel to grain (//) direction of samples with moisture content at FSP. The minimum TC value of Scots pine was 0.193 W/mK in the perpendicular to grain (⊥) direction of the oven-dried samples. Also, the maximum was 0.340 W/mK in the parallel to grain (//) direction of samples with MC at FSP. Accordingly, the maximum values for black alder and Scots pine were about 155% and 76% higher than the lowest ones, respectively.

Since the wood material is anisotropic, it has different characteristic features in different directions. Thermal conductivity, which is one of these features, also varies according to direction (Suleiman et al., 1999). The heat transfer of the wood material in parallel with the fibres is higher than the one in the transverse direction. This may be related to the orientation of the molecular chains inside the cell wall. Long-chain linear polymers (cellulose) making up the cell wall form structures parallel to the longitudinal cell axis called microfibril bundles. Heat energy is easily transferred on these bundles. On the other hand, since the air in the cell lumens is a good insulator, the conductivity of heat energy in the tangential direction is relatively lower (Parrott and Stuckes, 1975; Suleiman et al., 1999).

According to ANOVA results, the MC is statistically significant on the TC in both wood materials. According to the results of Duncan test which was carried out to detect the differences among the groups, there was a significant difference at 95% confidence level in both wood type. As the moisture content increased the TC value increased in both parallel to (//) and perpendicular to grain (⊥) direction in both wood types.

The minimum modulus of rupture value of black alder was 44.85 N/mm^2 in oven-dried samples while the maximum was 96.90 N/mm^2 in samples with MC at FSP. Also, the minimum modulus of rupture value of Scots pine was 37.57 N/mm^2 in oven-dried samples while the maximum was 80.35 N/mm^2 in samples with moisture content at FSP. The ANOVA results showed a significant difference for modulus of rupture values in both wood materials. All density groups separated according to the moisture content were significantly different according to Duncan's multiple range test (< 0.05) in both wood types. From the obtained results, it can be clearly seen that there is an inverse relationship between the amount of moisture and static bending strength.

The minimum impact bending strength value of black alder was 17.44 J/cm^2 in oven-dried samples while the maximum was 35.86 J/cm^2 in samples with moisture content at FSP. Also, the minimum impact bending strength value of Scots pine was 16.85 J/cm^2 in oven-dried samples while the maximum was 39.78 J/cm^2 in samples with moisture content at FSP. The ANOVA results showed a significant difference for impact bending strength values in both wood materials. All density groups separated according to the moisture content were significantly different according to Duncan's multiple range test (<0.05) in black alder samples However, while air dry and oven dry samples were included in the same group, samples with moisture at FSP was in different homogeneity group in the Scots pine samples.

Table 2. Thermal conductivity and mechanical properties of samples

Properties	Black Alder						Scots pine					
	Thermal Conductivity (W/mK)		Modulus of Rupture (N/mm^2)	Impact Bending Strength (J/cm^2)	Compression strength (N/mm^2)		Thermal Conductivity (W/mK)		Modulus of Rupture (N/mm^2)	Impact Bending Strength (J/cm^2)	Compression strength (N/mm^2)	
	//[c]	⊥[c]			⊥	//	//	⊥			⊥	//
Oven Dry Density (g/cm^3)	0.207A[a] (0.004)[b]	0.119A (0.035)	96.90A (7.754)	17.44A (0.026)	12.49A (0.274)	72.06A (0.112)	0.210A (0.005)	0.193A (0.009)	80.35A (6.455)	16.85A (0.153)	9.73A (0.985)	73.95A (5.263)
Air Dry Density (g/cm^3)	0.273B (0.009)	0.166B (0.036)	66.41B (5.215)	20.09B (0.041)	7.72B (0.116)	30.60B (1.105)	0.253B (0.007)	0.223B (0.008)	66.77B (3.415)	17.44A (0.205)	7.99B (0.658)	36.66B (3.278)
Density at FSP (g/cm^3)	0.305C (0.005)	0.190C (0.041)	44.85C (3.684)	35.86C (0.427)	5.30C (0.129)	21.84C (0.700)	0.340C (0.005)	0.294C (0.02)	37.57C (4.012)	39.78B (0.221)	4.36C (0.412)	22.81C (2.194)

[a] Groups with the same letters in each column indicate that there is no statistical difference ($p<0.05$) between the samples according to the Duncan test.

[b] Values in parentheses are standard deviation

[c] // : Parallel to grain, ⊥: Perpendicular to grain

The minimum compression strength values of black alder and Scots pine samples were 5.30 N/mm^2 and 4.36 N/mm^2 in the perpendicular to grain (⊥) direction of samples with moisture content at FSP, respectively. The maximum compression strength values of black alder and Scots pine were 72.06 N/mm^2 and 79.95 N/mm^2 in the parallel to grain (//) direction of oven-dried samples, respectively. The ANOVA results showed that moisture content was a significant factor on the compression strength. All density groups separated according to the moisture content were significantly different according to Duncan's multiple range test (< 0.05) in both wood types.

Conclusion

In this study, the effects of moisture and grain direction on the TC and mechanical properties of wood materials were investigated.

The TC was found to be 72% higher in the direction parallel to the grain (//) compared to the direction perpendicular to the grain (⊥) in the air-dried black alder samples. Similarly, it was 60% and 64% higher in samples with moisture at FSP and oven-dried, respectively. In Scots pine samples. The increase in TC according to grain direction was observed as 9%, 13% and 24% in samples with moisture at FSP, oven-dried and air-dried, respectively.

When the percentage changes obtained from the two species are compared with each other, changes in Scots pine are quite higher than in black alder. The basic reason for this is that the difference of the tracheid structures in black alder and Scots pine. Also, Scotch pine is an angiosperm while black alder is a gymnosperm, and this may be another reason.

Modulus of rupture was found to be 53% lower in the black alder samples with moisture at FSP than oven-dried ones. In Scots pine, for Modulus of rupture values, FSP density value was found 53 % less than over dry density similarly.

In conclusion, it was observed that when moisture content of samples increases, TC of perpendicular to grain (⊥) and parallel to grain (//) also increase. And when TC values increase, with compression strength of perpendicular (⊥) and parallel to grain (//), bending strength decrease but impact bending strength increase.

Acknowledgments

This study was funded by TUBITAK, The Scientific and Technological Research Council of Turkey, scientific research project with the grant number 114O644.

Ethics Committee Approval

N/A

Peer-review

Externally peer-reviewed.

Author Contributions

Conceptualization: Ş.K.; Investigation: Ş.K., M.K.; Material and Methodology: Ş.K., M.K; Supervision: Ş.K.; Writing-Original Draft: Ş.K.; Writing-review & Editing: Ş.K., M.K; Other: All authors have read and agreed to the published version of manuscript.

Conflict of Interest

The authors have no conflicts of interest to declare.

Funding

The authors declared that this study has received no financial support.

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