Mechanical Properties of Earlywood and Latewood Sections of Scots Pine Wood

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The aim of this study was to determine the mechanical properties of earlywood (EW) and latewood (LW) sections of Scots pine (*Pinus sylvestris* L.) wood, and determine the relationship between calculated and measured values. The bending strength, modulus of elasticity in bending, and the tensile strength of EW and LW sections were determined. The mechanical properties were calculated using EW and LW mechanical properties and LW proportion. Also, mechanical properties were determined in standard size samples and compared to the calculated properties. In earlywood and latewood sections, the bending strength was 37.3 MPa and 93.9 MPa, the modulus of elasticity in bending was 1557.6 MPa and 3600.4 MPa, and the tensile strength was 58.6 MPa and 189.6 MPa, respectively. The results showed that the LW section had higher mechanical properties than those of the EW section for all of the measured mechanical properties. The calculated bending strength, modulus of elasticity, and tensile strength values were 53.3 MPa, 2133.7 MPa, and 95.5 MPa, respectively. The calculated bending strength and modulus of elasticity values were lower compared to the measured values, while the calculated tensile strength values were higher than that of the measured values.

Keywords: Scots pine; Earlywood; Latewood; Bending strength; Modulus of elasticity; Tensile strength

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INTRODUCTION

Scots pine is an important tree species native to Eurasia. In Turkey, it covers approximately 6.8% (1.5 million ha) of the total Turkish forestland. Moreover, it exhibits superior technological properties and has a high potential for utilization.

Trees form new cells each year called annual growth rings or growth rings. The growth rings have two different parts. The inner part of the growth ring first formed in the growing season is called earlywood (EW), and the outer part formed later in the growing season is called latewood (LW). The actual time of the formation of these two parts of a ring may vary with environmental and weather conditions. The EW is characterized by cells with relatively large cavities and thin walls. The LW cells have smaller cavities and thicker walls. The transition from EW to LW may be gradual or abrupt, depending on the kind of wood and the growing conditions at the time it was formed. The different densities of EW and LW are related to different cell wall diameters and thickness (Miller 1999).

When growth rings are prominent, as in most softwoods and ring-porous hardwoods, the EW differs markedly from LW in physical properties. The EW is lighter in weight, softer, and weaker than LW. Because of the greater density of LW, the percentage of LW is sometimes used to judge the strength of the wood (Miller 1999). The density and microfibril angle (MFA) values of EW and LW have an important effect on the mechanical properties of wood. The density of LW is higher compared to EW. Jeong *et al.* (2009) determined that the LW density from growth ring numbers 1 to 10 and from growth ring numbers 11 to 20 was 74% and 26% higher than that of EW. The MFA in the S2 layer of the EW are generally higher compared to the LW MFA. Roszyk (2014) determined that the MFA were 16.4° and 9.0°, and the average density was 235 kg/m^3 and 665 kg/m^3 in the EW and LW of Scots pine, respectively.

Micro-scale sized samples have been used to determine the mechanical properties of earlywood and latewood sections, wood strands, and fibers (Groom *et al*. 2002; Mott *et al*. 2002; Cramer *et al*. 2005; Kretschmann *et al*. 2006; Hindman and Lee 2007; Jeong 2008; Jeong *et al*. 2009; Lanvermann *et al*. 2014; Roszyk *et al*. 2016). Cramer *et al*. (2005) determined the elastic properties of EW and LW (longitudinal modulus of elasticity, shear modulus) in loblolly pine wood. They found that the elastic properties varied by ring and height; the modulus of elasticity increased with height while the shear modulus decreased with height.

Kretschmann *et al.* (2006) determined the modulus of elasticity (MOE) and shear modulus of earlywood and latewood of loblolly pine. The dimensions of the samples were 1 mm × 1 mm × 30 mm, and were obtained from different growth ring numbers and different heights of the trees. The MOE of EW and LW was 3.5 GPa and 8.1 GPa at the 1.5 m height of the tree, respectively. Hindman and Lee (2007) measured the bending and tensile properties of loblolly pine (*Pinus taeda*) strands considering the earlywood and latewood sections.

The bending test samples were 33.0 mm long, 11.0 mm wide, and 0.68 mm thick, and the tension test samples were 60 mm long, 0.66 mm thick, and 4.58 mm wide for earlywood and 3.3 mm wide for latewood. The loading rate was 0.127 mm/min. They found that the tensile strength was 27.5 MPa and 48.8 MPa, the bending strength was 35.3 MPa and 88.3 MPa, and the modulus of elasticity in bending was 1.92 GPa and 6.54 GPa in EW and LW, respectively.

Jeong *et al.* (2009) measured the tensile strength and tensile modulus of EW and LW from loblolly pine wood. They concluded that the tensile strength of growth rings 1 through 10 and 10 through 20 were 18.69 MPa and 25.01 MPa for EW and 34.21 MPa and 33.47 MPa for LW, respectively.

Roszyk *et al*. (2016) determined the tensile properties of EW and LW of scots pine wood in both a dry and wet state. They found that the tensile strength of EW and LW was 51.9 MPa and 150.1 MPa for growth rings 31 through 39, 56.9 MPa and 136.0 MPa for growth rings 43 through 49, and 52.2 MPa and 174.4 MPa for growth rings 60 through 66 in 8% moisture content, respectively.

In previous studies, some mechanical properties of EW and LW sections of different wood species were investigated. Most of the previous studies were about the tensile properties (tensile strength and tensile modulus) of EW and LW sections of wood. Also, there have been no studies dealing with the relationship between the calculated and measured mechanical properties of wood species. The aim of this study was to determine the mechanical properties of EW and LW sections of Scots pine wood and determine the relationship between calculated and measured mechanical properties.

EXPERIMENTAL

Materials

Sample trees were harvested from Bolu Forest Enterprises in the northwestern part of Turkey. Eight trees with straight stems were selected as the sample trees. Table 1 presents the properties of the sample trees and sampling area. Logs of 3 m in length were cut from each tree at a height of 0.30 m, and then 6-cm-thick planks, including the central pith, were cut from these logs. Standard-size test samples were prepared from lumber cut from these logs according to ISO 3129 (2012). The wood parts were cut from the planks in 3 cm lengths to measure EW and LW widths. The EW and LW samples were randomly selected from the large growth rings of the planks because of sample dimensions and EW and LW widths. Figure 1 shows the preparation process of the test specimens. In order to reach a target moisture content of 12% prior to testing, all of the specimens were conditioned in a climate chamber at a temperature of 20 °C and a relative humidity of 65% until constant weights of specimens were provided.

Table 1. Properties of the Sample Trees and Sampling Area

Tree No.	Diameter of Tree at 1.30 m (cm)	Tree Age (year)	Altitude (m)	Aspect	Slope (%)
1	33	137	1540	Northeast	40
2	34	135			
3	34	144			
4	37	127			
5	34	94			
6	32	135			
7	36	123			
8	35	130			

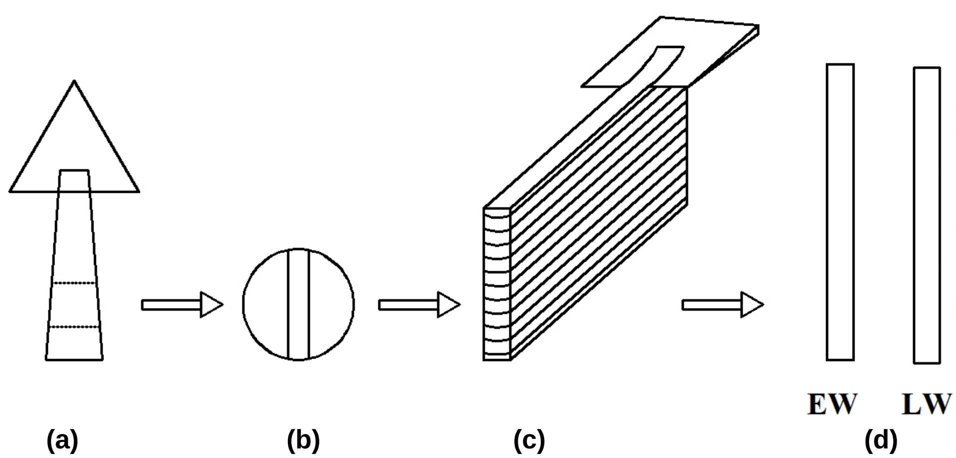

Fig. 1. The preparation process of the EW and LW test specimens; a) Cutting the logs, b) Cutting the 6-cm-thick planks from logs, c) Cutting the EW and LW samples from planks, and d) The EW and LW samples

Methods

Determination of ring properties

The EW and LW widths were measured to the nearest 0.01 mm using the LINTAB (FrankRinn S.A., Heidelberg, Germany) linear table and the TSAP Win program. The annual ring width and LW proportion were calculated from the EW and LW widths.

Measured mechanical properties

Standard sized specimens were cut according to ISO standards to determine the bending strength (ISO 13061-3, (2014)), modulus of elasticity in bending (ISO 13061-4, (2014)), and tensile strength parallel to the grain (ISO 13061-6, (2014)). A Lloyd universal test machine (Lloyd Instruments, LS100, Florida, USA) with a 10 kN load cell was used for the standard size tests.

The standard-size test specimens were prepared at dimensions of 20 mm × 20 mm × 360 mm for bending, and 15 mm × 50 mm × 400 mm for tension testing. In the three-point bending test, the load was applied in the direction tangential to the annual rings, and the span/thickness ratio was 15.

Earlywood and latewood mechanical properties

The bending and tension tests were performed on the EW and LW samples. The tests were performed using a Zwick universal test machine (Zwick GmbH & Co., ZO50TH, Ulm, Germany) with a 100 N load cell for the bending test and a 1kN load cell for tension tests.

The same standards were used as a guide for the EW and LW samples. The bending test samples were approximately 50.0 mm long, 5.0 mm wide, and 0.6 mm to 1.2 mm thick for EW and LW. The tests were performed with a three-point bending fixture. The same span/thickness ratio for the standard size bending tests was used for the EW and LW bending samples.

The tension test specimens were approximately 50 mm long, 5.0 mm wide, and 0.8 mm to 1.2 mm thick. The width of the sample was reduced to 0.8 mm with a sanding drum to get a dog-bone shape. From the ultimate load, the tensile strength was calculated. The gauge length was 30 mm for the EW and LW tension specimens.

Calculated mechanical properties

The bending strength, tension strength, and modulus of elasticity in bending were calculated using Eqs. 1 and 2 (Kollmann and Côté 1968),

$$\sigma calc = \sigma_{EW} + s \times (\sigma_{LW} - \sigma_{EW}) \quad (1)$$

$$MOE_{calc} = MOE_{EW} + s \times (MOE_{LW} - MOE_{EW}) \quad (2)$$

where σ_{calc} is the calculated strength (MPa), σ_{EW} is the EW strength (MPa), σ_{LW} is the LW strength (MPa), s is the LW percentage (%), MOE_{calc} is the calculated modulus of elasticity, MOE_{EW} is the EW modulus of elasticity, and MOE_{LW} is the LW modulus of elasticity.

RESULTS AND DISCUSSION

The average EW, LW, annual ring widths, and LW percentage were calculated as 0.96 mm, 0.39 mm, 1.34 mm, and 28.2%, respectively (Table 2). Oktem (1994) determined that the annual ring width and LW percentage of Scots pine wood grown in the West Black Sea Region were 2.07 mm and 26%, respectively. These annual ring widths and LW percentage differences arose from the tree age and growth conditions, such as precipitation, temperature, aspect, soil characteristic, *etc*.

Table 2. EW Width, LW Width, Annual Ring Width, and LW Percentage of Scots Pine Wood

Tree Number	Number of measured annual rings	EW Width (mm)	LW Width (mm)	Annual Ring Width (mm)	LW Percentage (%)
1	134	0.99 (1.07)	0.78 (0.52)	1.77 (1.33)	44.3 (23.8)
2	132	0.78(0.84)	0.23 (0.19)	1.01 (1.00)	28.8 (10.7)
3	141	0.85 (0.30)	0.39 (0.24)	1.24 (0.47)	30.8 (8.8)
4	124	1.05 (0.40)	0.32 (0.17)	1.37 (0.47)	23.5 (8.0)
5	91	1.15 (0.46)	0.34 (0.14)	1.49 (0.56)	23.4 (6.2)
6	132	0.88 (0.55)	0.42 (0.20)	1.30 (0.71)	34.2 (8.0)
7	120	1.01 (0.57)	0.28 (0.25)	1.29 (0.73)	21.4 (7.6)
8	127	0.93 (0.34)	0.34 (0.14)	1.27 (0.42)	27.0 (7.8)
Average		0.95 (0.64)	0.39 (0.31)	1.34 (0.81)	30.9 (15)

***Note:** Values in the parenthesis are standard deviation

Table 3 indicates the bending strength values of EW and LW sections, calculated and measured. The average bending strength values of EW and LW sections were 37.3 MPa and 93.6 MPa, respectively.

The lower bending strength values of EW could be attributed to the lower density and higher MFA of EW compared to LW. Roszyk (2014) determined the lower density and the higher MFA values in EW of scots pine. The ratio of LW to EW bending strength was 2.51:1. Hindman and Lee (2007) determined a similar ratio in loblolly pine. They found it as 2.50:1.

Similarly, they also discovered greater bending strength values in LW of loblolly pine. They found that the bending strength values of EW and LW were 35.3 MPa and 88.3 MPa, respectively. The coefficient of variation (COV) of bending strength values were 28.1% and 30.0% for EW and LW, respectively. Similar higher the COV values were observed by Hindman and Lee (2007).

They also found higher COV values for LW compared to EW. The calculated and measured bending strength values were 53.3 MPa and 72.8 MPa, respectively. The results showed that the calculated bending strength value was 26.8% lower than measured bending strength.

Table 3. The EW, LW, Calculated, and Measured Bending Strength Values of Scots Pine Wood

Value	Number of Specimens	Arithmetic mean (MPa)	Standard Deviation	Minimum Value (MPa)	Maximum Value (MPa)	Coefficient of Variation (%)
EW	65	37.3	10.5	13.0	61.0	28.1
LW	65	93.9	28.2	56.6	174.3	30.0
Measured	402	72.8	9.7	45.6	105.4	13.3
Calculated	65	53.3	10.4	35.2	89.7	19.6

Table 4 depicts the modulus of elasticity values of the EW and LW sections, calculated and measured. The average EW and LW MOE values were 1.56 GPa and 3.6 GPa, respectively. The ratio of the LW to EW MOE was 2.31:1. Hindman and Lee (2007) and Megraw *et al*. (1999) reported that the average LW/EW ratio and bending modulus of loblolly pine was 3.41:1 and 2.3:1, respectively. The lower MOE values of EW could be attributed to the lower density and higher MFA of EW compared to LW. Similarly, the higher MOE values in LW were found by Hindman and Lee (2007) in loblolly pine. They found that the MOE values of EW and LW were 1.92 GPa and 6.54 GPa, respectively. The COV of modulus elasticity values were 28.6% and 34.6% for EW and LW, respectively. Similar higher COV values were observed in previous studies (Hindman and Lee 2007; Jeong *et al*; Cramer *et al*. 2005). The calculated and measured MOE values were 2.13 GPa and 9.92 GPa, respectively. The results showed that the calculated MOE value was 78.5% lower compared to the measured MOE.

Table 4. The EW, LW, Calculated, and Measured Modulus of Elasticity in Bending of Scots Pine Wood

Value	Number of Specimens	Arithmetic Mean (MPa)	Standard Deviation	Minimum Value (MPa)	Maximum Value (MPa)	Coefficient of Variation (%)
EW	51	1.56	0.44	0.71	2.52	28.6
LW	51	3.60	1.25	2.22	7.77	34.6
Measured	402	9.92	1.83	5.60	1.49	18.5
Calculated	51	2.13	0.51	1.31	3.39	23.9

The EW and LW calculated and measured tension strength values of Scots pine wood are shown in Table 5. The average EW and LW tension strength values were 58.6 MPa and 189.6 MPa, respectively. The ratio of the LW to EW tension strengths was 3.24:1. Hindman and Lee (2007) found that this ratio was 1.77:1 in loblolly pine. Similarly, greater tension strength values in LW were found by several researchers (Mott *et al*. 2002; Hindman and Lee 2007; Jeong *et al*. 2009; Roszyk *et al*. 2016). Mott *et al*. (2002) concluded that the tensile strength of the LW fibers was 73% greater than the EW fibers in southern pine. Roszyk *et al*. (2016) found that the tensile strengths of the EW and LW of scots pine were 51.9 MPa and 150.1 MPa for growth rings 31 through 39, 56.9 MPa and 136.0 MPa for growth rings 43 through 49, and 52.2 MPa and 174.4 MPa for growth rings 60 through 66 in 8% moisture content, respectively. Hindman and Lee (2007) found that the tension strength values of EW and LW in loblolly pine were 27.5 MPa and 48.8 MPa, respectively. Jeong *et al*. (2009) found that the tensile strength of growth rings 1 through 10 and 10 through 20 in loblolly pine was 18.69 MPa and 25.01 MPa for EW, and 34.21 MPa and 33.47 MPa for LW. The difference in the tensile strength of EW and LW could be attributed to the differences in density and MFA of EW and LW. Roszyk (2014) determined the MFA were 16.4° and 9.0°, and the average density was 235 kg/m^3 and 665 kg/m^3 in EW and LW of scots pine, respectively. The MFA in the S2 layer of the EW were generally higher compared to LW. Thus, the tensile strength of EW was usually lower than that of LW (Wimmer *et al*. 1997; Mott *et al*. 2002; Moliński and Krauss 2008; Roszyk 2014). In the small MFA values, the cellulose determined the behaviour of the wood under tensile stress. With increased MFA, the mechanical properties of cell walls became more dependent on the matrix incrusting the cellulose skeleton, *i.e*., on hemicelluloses and lignin (Bergander and Salmeen 2002; Barnett and Bonham 2004; Gindl and Schöberl 2004; Roszyk *et al*. 2013; Roszyk *et al*. 2016). The COV of tensile strength values were 28.5% and 33.7% for EW and LW, respectively. Similar higher COV values were observed in previous studies (Hindman and Lee 2007; Jeong *et al*; Cramer *et al*. 2005). The calculated and measured tension strength values were 95.5 MPa and 76.9 MPa. The results showed that the calculated tension strength value was 24.2% higher compared to measured tension strength.

Table 5. The EW, LW, Measured, and Calculated Tension Strength Values of Scots Pine Wood

Value	Number of Specimens	Arithmetic Mean (MPa)	Standard Deviation	Minimum Value (MPa)	Maximum Value (MPa)	Coefficient of Variation (%)
EW	50	58.6	16.7	24.1	98.8	28.5
LW	50	189.6	63.9	103.7	374.2	33.7
Measured	219	76.9	21.5	25.26	133.6	28.0
Calculated	50	95.5	18.6	58.0	143.3	19.5

CONCLUSIONS

1. The bending strength, modulus of elasticity in bending, and tensile strength values of LW were 2.51, 2.31, and 3.24 times higher than those of EW, respectively.
2. The highest difference between the EW and LW mechanical properties of Scots pine wood were observed in the tension strength.
3. The calculated bending strength and modulus of elasticity in bending values of Scots pine wood were 26.8% and 78.5% lower compared to the measured values while the tensile strength was 24.2% higher in the calculated values.

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