Intra-Ring Properties of Earlywood and Latewood Sections of Sessile Oak (*Quercus petraea*) Wood

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Strength attributes of isolated microscopic sections of earlywood (EW) and latewood (LW) tissues are evaluated for sessile oak (*Quercus petraea*). The properties measured at the micro-scale were then used to estimate the macroscopic strength characteristics of the wood. The bending strength, modulus of elasticity (MOE) in bending, and tensile strength of EW and LW sections were determined. The EW and LW ring width, annual ring width, and LW proportion were also determined. The estimated values were calculated using the EW and LW mechanical properties and LW proportions, while the measured values were determined using standard-sized test samples. The LW sections had higher values than the EW sections for all measured mechanical properties. The average EW and LW widths and LW proportion were 0.50 mm, 0.49 mm, and 49.3%, respectively. The estimated bending strength, MOE, and tensile strength values were 80.1 MPa, 2831.7 MPa, and 112.1 MPa, respectively. The estimated bending strength and MOE values were lower than the measured values, while the estimated tensile strength values were higher than the measured values.

Keywords: Oak wood; Earlywood; Latewood; Bending strength; Modulus of elasticity; Tensile strength

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INTRODUCTION

Oak is an important tree species that covers about 26.3% (5.9 million ha) of the total Turkish forestland. Oak wood has a density of about 0.75 g/cm^3, resulting in great strength and hardness. The wood is very resistant to insect and fungal attack because of its high tannin content. Oak wood is commonly used for furniture making, flooring, timber frame buildings, and veneer production.

The growth rings have two different sections. The inner part of the growth ring, formed first in the growing season, is called the earlywood (EW), and the outer part, formed later in the growing season, is the latewood (LW). The EW is characterized by cells with relatively large lumens and thin walls. The LW cells have smaller lumens and thicker walls (Miller 1999). The EW is lighter in weight, softer, and weaker than the LW. Miller (1999) stated that the proportion of LW, because of its greater density, is sometimes used to judge the strength of the wood. Cramer *et al.* (2005) reported that the strength and stiffness of EW is two to three times less than that of LW. Wood's mechanical properties are strongly influenced by the density and microfibril angle (MFA) values of EW and LW. The density of LW is higher than that of EW (Groom *et al*. 2002; Mott *et al*. 2002; Cramer *et al*. 2005; Jeong *et al*. 2009). Jeong *et al*. (2009) determined that the LW density of loblolly pine

(*Pinus taeda*) was higher than that of the EW. The MFAs in the S2 layer of EW are generally higher compared to LW MFAs (Roszyk 2014).

Wood is a widely used construction material because of its excellent mechanical properties. The major factors influencing wood's mechanical properties include the structure and technological quality of its cell walls (Roszyk *et al*. 2016). Determining the properties of EW and LW layers is important for understanding the micro-scale behavior of wood that affects the properties and the utilization of wood and wood-based materials (Hindman and Lee 2007; Jeong 2008). In addition, the identification of the intra-ring properties of wood provides inputs to finite element models (Jeong 2008). One important component in the production of composite materials is the prediction of mechanical properties based on the individual strand or fiber properties of the constituents. The understanding of EW and LW properties of wood fiber sources enables more refined modeling efforts to predict composite properties. Developing methods to predict their mechanical properties could elucidate the role of these properties in wood product quality and performance (Kretschmann *et al*. 2006).

Micro-sized samples have been used to determine the mechanical properties of EW and LW sections, wood strands, and fibers (Groom *et al.* 2002; Mott *et al*. 2002; Cramer *et al*. 2005; Kretschmann *et al*. 2006; Zink-Sharp and Price 2006; Hindman and Lee 2007; Jeong 2008; Jeong *et al*. 2009; Lanvermann *et al*. 2014; Roszyk *et al*. 2016; Büyüksarı *et al*. 2017a). In these studies, some mechanical properties of EW and LW sections of different wood species, especially softwoods, were examined, and most of these were concerned with the tensile properties (tensile strength and tensile modulus) of the EW and LW sections of wood. Roszyk *et al*. (2016) investigated the tensile properties of EW and LW and compared the estimated and measured values of Scots pine (*Pinus sylvestris* L.) wood. In another previous study (Büyüksarı *et al.* 2017a), the mechanical properties of Scots pine EW and LW were investigated. However, to date, there has been no investigation of the mechanical properties of EW and LW sections of oak wood, which is a ring-porous hardwood species, and information on the comparison of the estimated and measured mechanical properties of this wood species is also limited. Thus, the aim of this study was to compare the estimated and measured mechanical properties of EW and LW sections of sessile oak (*Quercus petraea*).

EXPERIMENTAL

Materials

Sample trees were harvested from Duzce Forest Enterprises in Duzce Province in northwestern Turkey. Five trees with straight stems were selected as the sample trees. Table 1 presents the properties of the sample trees and the sampling area.

Table 1. Properties of the Sample Trees and Sampling Area

Tree No.	Diameter of Tree at 1.30 m (cm)	Tree Age (years)	Altitude (m)	Aspect	Slope (%)
1	34	203	670	East	60
2	39	207			
3	40	193			
4	41	214			
5	40	204			

The sampling procedure was applied as reported previously by the authors (Büyüksarı *et al*. 2017a). All specimens were conditioned in a climate chamber at a temperature of 20 ^{o}C and a relative humidity of 65% for three weeks before testing.

Methods

Determination of ring properties

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

Measured mechanical properties

The bending strength (ISO 13061-3, 2014), MOE in bending (ISO 13061-4, 2014), and tensile strength parallel to the grain (ISO 13061-6, 2014) were determined. A Lloyd universal testing machine (Lloyd Instruments, LS100, Largo, FL, USA) with a 10-kN load cell was used for the standard-sized tests. The standard-sized test specimens were prepared at dimensions of 20 × 20 × 360 mm for bending and 15 × 50 × 400 mm for tensile testing.

Earlywood and latewood mechanical properties

The bending and tensile sample sizes and test procedures were followed as reported by Büyüksarı *et al.* (2017a). The 50 samples for EW and LW bending and tensile tests, and 290 and 233 samples for measured bending and tensile tests, respectively, were prepared. The bending and tensile tests were performed on the EW and LW samples using a Zwick universal testing machine (Zwick GmbH & Co., ZO50TH, Ulm, Germany) with a 100-N load cell for bending tests and a 1-kN load cell for tensile tests. The same standards were used as a model for the EW and LW samples.

Estimated mechanical properties

Similar equations for the calculation of the bending strength, tensile strength, and MOE in bending were used in the present work as reported by Büyüksarı *et al.* (2017a).

RESULTS AND DISCUSSION

The average EW, LW, and annual ring widths and LW proportion of sessile oak wood were calculated as 0.50 mm, 0.49 mm, 0.99 mm, and 49.3%, respectively (Table 2). Gursu (1966) determined that the annual ring width of oak wood grown in the Karabuk region was 1.58 mm for trees aged 97 to 156 years and 0.80 mm for trees aged 186 to 247 years. The proportion of LW was determined to be 66% in *Quercus faginea* by Knapic *et al*. (2011) and 61% in *Quercus suber* by Knapic *et al*. (2008). These annual ring width and LW proportion differences can be a result of growth conditions such as precipitation, temperature, aspect, soil characteristics, *etc*.

The estimated, measured, EW, and LW bending strength values of sessile oak wood are shown in Figure 1. The average EW and LW bending strength values were 63.7 with a COV (coefficient of variation) of 14.8% and 96.6 MPa with a COV of 14.8%, respectively. The ratio of LW to EW bending strength was 1.52:1. In loblolly pine this ratio was calculated as 2.50:1 by Hindman and Lee (2007).

Table 2. The EW width, LW width, annual ring width, and LW percentage of oak wood

Tree Number	Number of Measured Annual Rings	EW Width* (mm)	LW Width* (mm)	Annual Ring Width* (mm)	LW Percentage (%)
1	200	0.53 (0.17)	0.50 (0.17)	1.03 (0.30)	48.5
2	204	0.48 (0.16)	0.48 (0.23)	0.95 (0.34)	50.0
3	190	0.55 (0.24)	0.47 (0.24)	1.02 (0.45)	45.9
4	211	0.48 (0.23)	0.47 (0.23)	0.94 (0.43)	49.5
5	201	0.47 (0.17)	0.52 (0.27)	0.99 (0.42)	52.4
Average		0.50	0.49	0.99	49.3

***Note:** Values in parentheses are standard deviation

The lower ratio in the current study can be attributed to the differences of EW and LW in different wood species. Loblolly pine is a softwood species with the difference in the density of EW and LW being generally high, while in the ring-porous oak wood species, the difference in density of EW and LW is generally low. Cown and Parker (1978) concluded that the softwoods vary more than hardwoods in intra-ring density contrast. Knapic *et al*. (2011) stated that the LW density of oak (*Quercus faginea*) was 26.6% higher than that of the EW. Hindman and Lee (2007) determined that the LW density of loblolly pine wood was 91.9% higher than that of the EW. Another reason of the differences between the EW and LW mechanical properties can be the MFAs of the LW and EW. Lanvermann *et al*. (2014) stated that in addition to density, differences in the mechanical properties between the EW and LW are related to MFAs of the EW and LW.

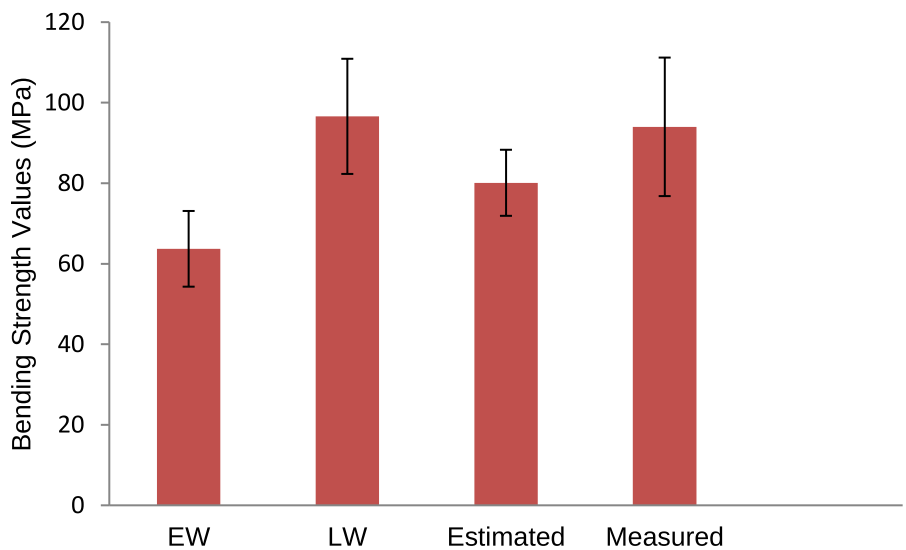

Fig. 1. The EW, LW, estimated, and measured bending strength values of oak wood

The LW bending strength value was 51.6% greater than the EW value. Similarly, greater LW bending strength values were found in loblolly pine by Hindman and Lee (2007), who determined that the bending strength values of EW and LW were 35.3 and 88.3 MPa, respectively. The estimated and measured bending strength values were found to be 80.1 and 94.0 MPa, respectively. The bending strength value estimated based on the analysis of isolated EW and LW tissues was 14.8% lower than the measured bending strength. Similar results were found by Büyüksarı *et al*. (2017a) who reported that the estimated bending strength of Scots pine wood was 26.8% lower than the measured bending strength.

The EW, LW, estimated, and measured modulus of elasticity (MOE) in the bending values of sessile oak wood are shown in Fig. 2. The average EW and LW MOE values were 2222 MPa with a COV of 22.1% and 3452 MPa, respectively. The ratio of LW to EW MOE was 1.55:1. Megraw *et al*. (1999) and Hindman and Lee (2007) reported the average bending modulus ratios of LW/EW as 3.41:1 and 2.3:1, respectively. The lower ratio in the current study can be attributed to the wood species.

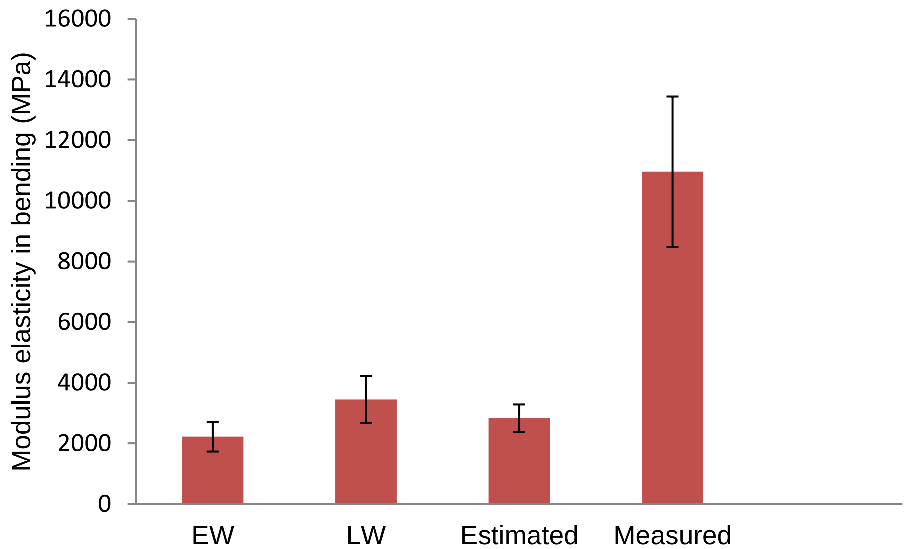

Fig. 2. The EW, LW, estimated, and measured MOE values of oak wood

The LW MOE value was 55.4% greater than the EW value. Similarly, higher MOE values in LW were found in loblolly pine by Hindman and Lee (2007), who determined that the MOE values of EW and LW were 1.92 and 6.54 GPa, respectively. Kretschmann *et al*. (2006) found the MOE of loblolly pine EW and LW at the 1.5 m height of the tree to be 3.5 and 8.1 GPa, respectively. The estimated and measured MOE values were determined as 2832 MPa with a COV of 15.9% and 10961 MPa with a COV of 22.6%, respectively. The results showed that the estimated MOE value was 74.2% lower than the measured MOE. Similar results were found by Büyüksarı *et al.* (2017a) who found that the estimated MOE value of Scots pine wood was 78.5% lower than the measured MOE.

For the MOR and MOE values, the lower estimated values compared to measured values can be attributed to the sample dimensions and volume. In this study, micro-size test samples were used to calculate the estimated values and standard-size test samples were used for the measured values. The previous studies showed that the micro-size test samples had the lower MOR and MOE values compared to standard-size samples (Deomano 2001; Büyüksarı *et al*. 2016, 2017b). Buyuksari *et al*. (2017b) observed that the MOR and MOE values of the oak wood micro-size specimens were 40% and 75% lower than those of the standard–size specimens, respectively. Similarly, Deomano (2001) stated that the MOR and MOE values of micro-size specimens were lower than those of standard-size samples for southern yellow pine, sweet gum, and yellow poplar, except for the MOR of yellow poplar. The mechanical properties of specimens are dependent on the specimen dimensions. According to theory of the size effect (weakest link theory), the strength is dependent on the size of highly stressed volume, and lower strength values can be observed in a member of large volume compared to small volume member (Weibull 1951). Madsen and Buchanan (1986) also stated that the size effect is dependent on wood species.

Figure 3 shows the EW, LW tensile strength values, along with the estimated and measured tensile strength values of sessile oak wood. The average EW and LW tensile strength values were found to be 76.8 MPa with a COV of 20.7% and 148.0 MPa with a COV of 25.3%, respectively, and the ratio of LW to EW tensile strength was 1.93:1. Hindman and Lee (2007) found this ratio to be 1.77:1 in loblolly pine. The LW tensile strength value was 92.7% greater than the EW value. Similarly, greater tensile strength values in LW were reported by several other researchers (Hindman and Lee 2007; Jeong *et al*. 2009; Roszyk *et al*. 2016). The difference in the tensile strength of EW and LW can be attributed to the differences in density and MFA of EW and LW. The MFAs in the S2 layer of EW are generally higher compared to LW. Thus, the tensile strength of EW is usually lower than that of LW (Wimmer *et al*. 1997; Moliński and Krauss 2008; Roszyk 2014). When the MFA values are low, the cellulose determines the behavior of the wood under tensile stress. With increasing MFA, the mechanical properties of the cell walls become more dependent on the matrix incrusting the cellulose skeleton, *i.e.*, on the hemicelluloses and lignin (Bergander and Salmén 2002; Barnett and Bonham 2004; Gindl and Schöberl 2004; Roszyk *et al*. 2013; Roszyk *et al*. 2016).

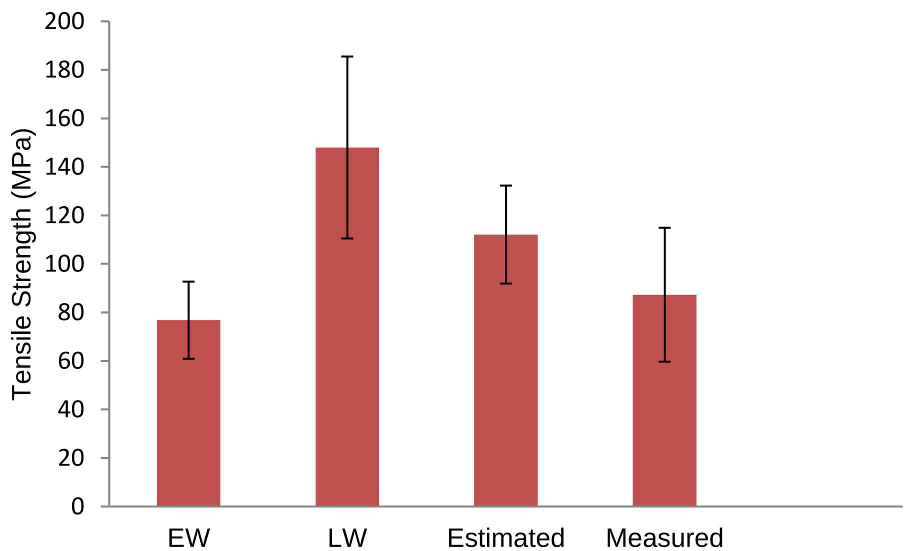

Fig. 3. The EW, LW, estimated, and measured tensile strength values of oak wood

The estimated and measured tensile strength values were found to be 112.1 MPa with a COV of 18.0% and 87.3 MPa with a COV of 31.6%, respectively. These results showed that the estimated tensile strength value was 22.1% higher compared to the measured tensile strength. This is compatible to Weibull's theory, which states that with increasing volume the strength decreases. Similarly, higher estimated tensile strength values were found in pine wood by Roszyk *et al.* (2016) for growth rings 60 to 66 under both dry (8%) and wet (> fiber saturation point) conditions, while lower estimated values were observed for growth rings 31 to 39 and 43 to 49. Similar results were also found by Büyüksarı *et al*. (2017a,b) in Scots pine and oak wood. Büyüksarı *et al*. (2017a,b) concluded that the tensile strength values of the micro-size oak and scots pine wood were 5.2% and 19% higher compared to the standard-size samples, respectively. However, in some previous studies it has been found that the tensile strength of micro samples was lower compared to standard samples (Price 1976; Cai *et al*. 2007). Cai *et al*. (2007) reported that the tensile properties of willow, yellow poplar, red oak, and loblolly pine wood strands were significantly lower than those of standard-size wood. Price (1976) observed similar results for micro-size sweet gum specimens. The gage length, sample thickness, loading rate and sample shape (dog- bone or rectangle shape) affect tensile strength of the samples. Kohan *et al*. (2012) stated that the dog-bone shaped specimens had 16% higher tensile strength than the rectangular specimens. Price (1976) concluded that tensile strength increased as gauge length increased. Jeong *et al.* (2008) found that tensile strength generally increased as the thickness increased.

CONCLUSIONS

1. The bending strength, MOE in bending, and tensile strength values of the sessile oak LW were 52%, 55%, and 93% higher, respectively, than those of the EW.
2. The greatest differences between the EW and LW mechanical properties of sessile oak wood were observed in the tensile strength.
3. The estimated bending strength and MOE in bending values of sessile oak wood were 15% and 74% lower, respectively, than the measured values, while the estimated values for tensile strength were 22% higher.

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