Effects of Moisture Content on Mechanical Properties of Micro-size Oak Wood

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Effects of moisture content (MC) were investigated for the mechanical properties of oak wood (*Quercus petraea* Liebl.) using micro-size test specimens. The micro-size specimens for bending, tensile, and compression tests were prepared and divided into five groups. Each group was conditioned at a different relative humidity and temperature to achieve MC values of 8%, 12%, 16%, 20%, and above-fiber-saturation-point MCs. After conditioning, the bending strength, modulus of elasticity (MOE) in bending, tensile strength, and compression strength values were determined. The results showed that MC had statistically significant effects on all the measured mechanical properties in the micro-size oak wood samples. The greatest decrease was observed for the compression strength, while the lowest decrease was observed for the tensile strength, when MC increased. The changing rates induced by 1% MC were calculated as 3% for bending strength, 2.5% for the MOE, 2.0% for the tensile strength, and 3.1% for the compression strength.

Keywords: Size effect; Moisture content; Changing rate; Flexural properties; Tension; Compression; Strength

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INTRODUCTION

Structural-size, standard-size (small and clear), micro-size, and cellular-size specimens have all been used to determine the mechanical properties of wood. Sample dimensions and volume have important effects on the mechanical properties of wood. This is called "size effect" or "weakest link theory" (Weibull 1951). According to this theory, the strength is dependent on the size of the highly stressed volume. The basis for this theory is that there is a greater probability that a region of low strength will occur in a sample of large volume than in a sample of small volume. This region of low strength is assumed to cause complete failure of the sample (Weibull 1951).

In recent years, the use of the micro-size specimens to determine the mechanical properties of wood is gaining prominence. Micro-size samples have some advantages in determining the mechanical properties of wood (Büyüksarı *et al*. 2016). Additionally, identification of wood's micro-scale behavior provides inputs to finite element models and predictions of the mechanical properties of composite materials based on the individual particle, strand, and fiber properties (Jeong 2008). Several previous studies have used micro-size specimens to evaluate the mechanical properties of earlywood and latewood sections, wood strands, and fibers (Plagemann 1982; Hunt *et al*. 1989; Deomano 2001; Deomano and Zink-Sharp 2004; Wu *et al*. 2005; Zink-Sharp and Price 2006; Cai *et al*. 2007; Hindman and Lee 2007; Jeong 2008; Jeong *et al*. 2009; Roszyk *et al*. 2016). Recently, studies have focused on comparisons of the micro-size and standard-size mechanical properties, correlations between micro-size and standard-size specimens, and factors affecting the mechanical properties of the micro-size specimens (Roszyk *et al*. 2016; Büyüksarı *et al*. 2016; Büyüksarı 2017a,b; Büyüksarı *et al*. 2017a,b,c, 2018).

There have been several published studies dealing with the micro-size mechanical properties of oak wood. Büyüksarı *et al*. (2017b) determined the micro-mechanical properties of oak wood and compared them with standard-size (small and clear) samples. They found that the bending strength, the modulus of elasticity, and the compression strength of the micro-size samples were lower compared to the standard-size samples, while the tensile strength was greater in the micro-size samples. They also showed a positive linear regression between mechanical properties of the micro-size and standard-size specimens. Büyüksarı (2017a) investigated the effects of loading rate on the mechanical properties of micro-size oak wood. Büyüksarı *et al*. (2018) also investigated the intra-ring properties of earlywood and latewood sections of oak wood.

In micro-size samples, the effects of several factors (gauge length, thickness, loading rate, and sample geometry) on the mechanical properties of the wood have been examined (Price 1976; Jeong *et al*. 2008; Kohan *et al*. 2012; Büyüksarı 2017a,b). It is well known that moisture content (MC) affects the mechanical properties of wood (Gerhards 1982; Green and Kretschmann 1994; Kretschmann and Green 1996; Ozyhar *et al*. 2012; Güntekin and Aydın 2013). The mechanical properties of wood decrease as the MC increases below the fiber saturation point (FSP). Beyond the FSP, there are no significant changes in the mechanical properties of wood. An extensive discussion on the effects of MC on the mechanical properties can be found in Green and Kretschmann (1994). In standard-size samples, Güntekin and Aydın (2013) investigated the effects of MC on the mechanical properties of Turkish red pine (*Pinus brutia* Ten.). They determined the modulus of elasticity in bending, bending strength, tensile strength, elasticity in tension, compression strength, and elasticity in compression of the small clear wood samples at 0%, 8%, 17%, and 28% MCs. They concluded that, below the FSP, all measured mechanical properties increased exponentially with decreasing MC. However, in micro-size samples, there is limited information about the effects of MC on the mechanical properties of wood. Roszyk *et al*. (2016) investigated the tensile properties of earlywood and latewood of Scots pine in dry (8%) and wet (>FSP) states. They performed their measurements in microtome samples sliced from either earlywood or latewood and samples containing both earlywood and latewood. The objective of this study was to determine the effects of MC on the mechanical properties of oak wood in micro-size samples.

EXPERIMENTAL

Five oak trees (*Quercus petraea* Liebl.) with straight trunks were harvested from Düzce Forest Enterprises in northwestern Turkey. Logs 3 m in length were cut from each tree at a height of 0.30 m, and 6-cm-thick planks including the central pith were then cut from these logs. The samples were longitudinally cut into five parts to provide homogeneity, with each part used for a different moisture condition. Each group was conditioned at different relative humidities and temperatures to achieve 8%, 12%, 16%, 20%, and above-FSP equilibrium moisture contents (EMC) (Table 1).

Table 1. Conditioning Parameters

Relative Humudity (%)	Temperature (°C)	EMC (%)
44	30	8
65	20	12
80	20	16
89	25	20
Water immersion		>FSP

There is no standard regarding the preparation of micro-size test samples. Therefore, sample dimensions and loading rates vary from one study to another study. In previous studies, different dimensions and loading rates were used by researchers (Büyüksarı *et al.* 2017b). The dimensions of the prepared samples in this study were similar to our previous studies on the micro-size samples (Büyüksarı *et al.* 2016; Büyüksarı 2017a,b; Büyüksarı *et al.* 2017a,c).

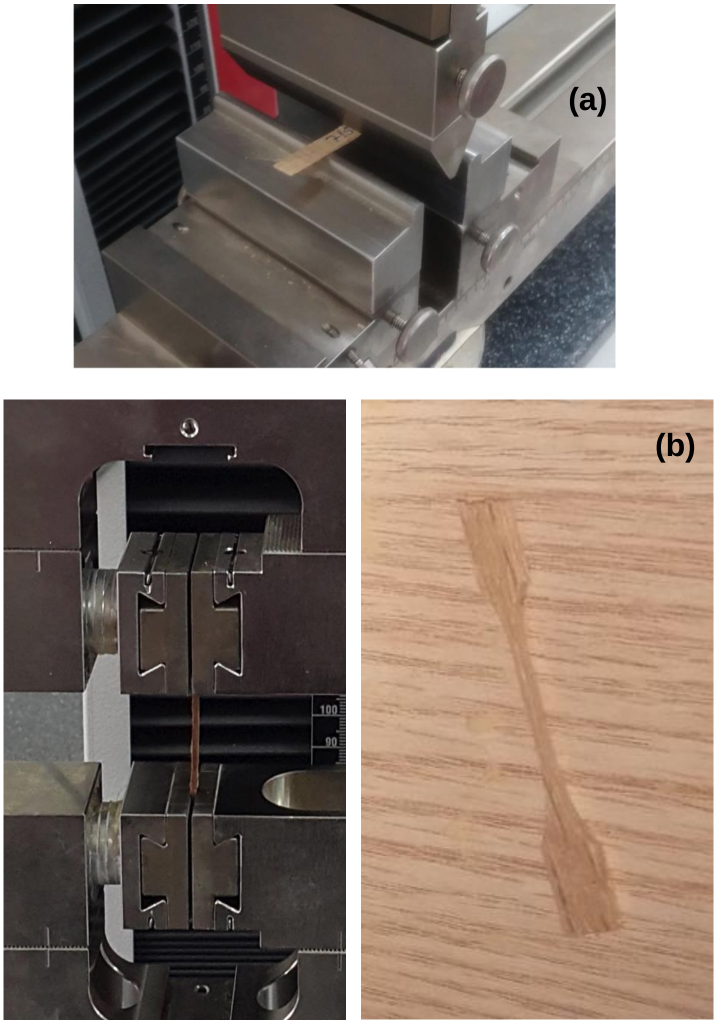

Fig. 1. (a) Bending test sample and test setup and (b) micro-size tensile test sample and test setup

The International Organization for Standardization (ISO) standards (ISO 13061-3, 2014 for bending strength, ISO 13061-4, 2014 for modulus of elasticity in bending, ISO

13061-6, 2014 for tensile strength parallel to grain, and ISO/DIS 13061-17, 2014 for compression strength parallel to grain) were used as a guide. The three-point bending test samples were prepared to dimensions of approximately 50.0 mm × 5.0 mm × 1 mm to 1.3 mm. In the three-point bending test, load was applied in the direction tangential to the annual rings, and the span/thickness ratio was 15. The micro-size tensile test samples were approximately 50 mm × 5.0 mm × 1 mm to 1.3 mm, and the width of the samples was reduced to 0.8 mm using a sanding drum. The gauge length was selected as 3 mm. The tensile strength was calculated from the ultimate load. The micro-size bending and tensile test samples and test setup are shown in Fig. 1. The micro-size compression test specimens had dimensions of 3 mm × 3 mm × 5 mm. All tests were performed with a Zwick universal testing machine (Zwick GmbH & Co., Z5.0 TH, Ulm, Germany) using a 100 N load cell for the bending and compression tests and a 1 kN load cell for the tension tests.

The average air-dry density values were measured in bending strength samples conditioned at 65% relative humidity and 20 °C temperature. It was determined as 0.675 $g.cm^{-3}$.

For the bending strength, modulus of elasticity in bending, tensile strength, and compression strength, all multiple comparisons were first subjected to an analysis of variance (ANOVA) at $p < 0.05$. Post hoc comparisons were conducted using Duncan's multiple range test.

RESULTS AND DISCUSSION

Table 2 lists some statistical parameters of the bending strengths and moduli of elasticity (MOE), along with Duncan's multiple range test results, of the micro-size oak wood specimens at different EMCs.

Table 2. Bending Strength, MOE, and Duncan's Test Results of Micro-size Oak Wood

Property	EMC (%)	*N*	*X* (MPa)	SD (MPa)	SE (MPa)	X_{min} (MPa)	X_{max} (MPa)	C_v (%)
Bending strength	8	100	89.3^A	25.4	2.5	42.8	157.9	28.4
	12	311	70.0^B	16.6	0.9	20.8	118.5	23.7
	16	100	63.0^C	15.3	1.5	23.4	100.7	24.3
	20	100	53.7^D	12.8	1.3	27.3	87.2	23.8
	> FSP	99	35.7^E	8.0	0.8	19.9	59.7	22.6
MOE	8	100	3537.9^A	1063.9	106.4	1737.6	6368.7	30.1
	12	311	2683.4^B	730.3	41.4	838.0	5120.0	27.2
	16	100	2651.1^B	788.7	78.9	985.0	4429.3	29.7
	20	100	2323.2^C	722.7	72.3	884.1	4310.9	31.1
	> FSP	99	1748.1^D	543.1	54.6	628.4	3373.3	31.1

N: number of specimens, *X*: average, SD: standard deviation, SE: standard error, X_{min}: minimum value, X_{max}: maximum value, C_v: coefficient of variation. Groups with identical capital letters in a column indicate that there is no statistical difference ($p < 0.05$) between the samples according to Duncan's multiple range test.

The greatest bending strength and MOE values (89.3 MPa and 3537.9 MPa) were measured in the 8% MC group. The lowest bending strength and MOE values (35.7 MPa and 1748.1 MPa) were found in the above-FSP MC group. The bending strength and MOE values significantly decreased when the MC increased. This result was attributed to swelling of the wood and decreasing of the cell wall ratio in the unit area and of the cohesive forces among the cellulose microfibrils; these phenomena occur when the MC increases below the FSP. It is well known that the mechanical properties of wood generally decrease with increasing MC below the FSP. Beyond the FSP, there are no significant changes in the mechanical properties of the wood. Because there is no further swelling in the wood, water fills the gaps between cell cavities, and capillary or free water in the cell cavities has no effect on the strength (Bozkurt and Göker 1996).

In this study, the changing rate of the oak wood bending strength was 3% per 1% change in MC. It has been reported that the changing rate of bending strength induced by 1% MC is 2.6% in Japanese cedar, China fir, western hemlock, red meranti, and Selangan batu and 3.9% in red oak (Wang and Wang 1999). The same rate was found as 1.3% in Turkish red pine by Güntekin and Aydın (2013). For the MOE, the changing rate induced by 1% MC was calculated as 2.5% in the oak wood. In previous studies, the changing rate was found as 0.58% in Japanese cedar, China fir, and red meranti, 1.2% in western hemlock and Selangan batu, 2.5% in red oak, and 1.8% in Turkish red pine (Wang and Wang 1999; Güntekin and Aydın 2013).

Significant differences between group averages for the bending strength values were determined individually by Duncan's multiple comparison tests. The results of Duncan's grouping are shown in Table 1 by letters. All groups showed statistically significant differences ($p < 0.05$) in their bending strengths from each other. For MOE, all groups except for the 12% and 16% EMCs showed statistically significant differences ($p < 0.05$) from each other.

The average air-dry bending strength and MOE of the oak wood were found as 70.0 MPa and 2683.4 MPa, respectively. The bending strength and MOE at 8% MC were 27.6% and 31.8% greater compared to their air-dry values, respectively. The bending strengths of the groups at 16%, 20%, and above-FSP MCs were, respectively, 10.0%, 23.3%, and 49.0% lower than that of the air-dry MC group. The MOE values of the groups at 16%, 20%, and above-FSP MCs were 1.2%, 13.4%, and 34.9% lower than that of the air-dry MC group, respectively. Güntekin and Aydın (2013) concluded that the bending strength and MOE of Turkish red pine wood decreased by 35% and 48%, respectively, when the MC increased from 0% to 28%.

Table 3 lists the average tensile strength values and Duncan's test results of the micro-size oak wood at different EMCs. The greatest tensile strength (104.1 MPa) was measured in the 8% MC group. Meanwhile, the lowest tensile strength (61.6 MPa) was found in the above-FSP MC group. The tensile strength values significantly decreased when the MC increased. This result was attributed to the swelling of the wood and decreasing of the cell wall ratio in the unit area and of the cohesive forces among the cellulose microfibrils. Significant differences between group averages for the tensile strength values were determined individually by Duncan's multiple comparison tests. The results of Duncan's grouping are shown in Table 3 by letters.

Table 3. Tensile Strength and Duncan's Test Results of Micro-size Oak Wood

EMC (%)	*N*	*X* (MPa)	SD (MPa)	SE (MPa)	X_{min} (MPa)	X_{max} (MPa)	C_v (%)
8	98	104.1^{A}	37.1	3.7	39.3	184.8	35.6
12	252	97.0^{AB}	34.4	2.2	31.1	233.4	35.5
16	99	93.9^{B}	37.1	3.7	29.4	205.0	39.5
20	99	96.3^{AB}	34.6	3.5	28.0	181.0	36.0
>FSP	99	61.6^{C}	22.7	2.3	13.1	119.9	36.9

N: number of specimens, *X*: average, SD: standard deviation, SE: standard error, X_{min}: minimum value, X_{max}: maximum value, C_V: coefficient of variation. Groups with identical capital letters in a column indicate that there is no statistical difference ($p < 0.05$) between the samples according to Duncan's multiple range test.

The average air-dry tensile strength of the oak wood was 97.0 MPa. The tensile strength at 8% MC was 7.3% greater than the air-dry tensile strength. The tensile strengths of the groups at 16%, 20%, and above-FSP MCs were 3.2%, 0.7%, and 36.5% lower than that of the air-dry MC group, respectively. The tensile strength decreased 40.8% as the MC increased from 8% to above the FSP. A similar decrease was found by Roszyk *et al*. (2016) in Scots pine wood. They found tensile strengths of 102.9 MPa and 57.8 MPa at 8% MC and in the wet state, respectively, with the tensile strength decreasing 43.8% as the MC increased from 8% to above the FSP. The changing rate of the oak wood tensile strength induced by 1% MC was calculated as 2.0%. It was the lowest changing rate among the mechanical properties measured in this study. The same rate was found as 0.7% in Turkish red pine by Güntekin and Aydın (2013). Similar to these findings, they stated that the tensile strength was the least affected variable by MC.

Table 4 lists the compression strengths and Duncan's test results of the micro-size oak wood at different EMCs. The greatest compression strength (60.5 MPa) was measured in the 8% MC group. Meanwhile, the lowest compression strength (22.7 MPa) was found in the above-FSP MC group.

Table 4. Compression Strengths and Duncan's Test Results of Micro-size Oak Wood

EMC (%)	*N*	X (MPa)	SD (MPa)	SE (MPa)	X_{min} (MPa)	X_{max} (MPa)	C_v (%)
8	98	60.5 A	12.9	1.3	35.8	87.7	21.4
12	327	45.5 B	9.2	0.5	25.6	70.7	20.2
16	99	43.5 B	8.5	0.9	28.1	68.5	19.5
20	100	36.8 C	8.2	0.8	23.4	73.3	22.2
>FSP	94	22.7 D	3.4	0.4	14.7	31.9	15.2

N: number of specimens, *X*: average, SD: standard deviation, SE: standard error, X_{min}: minimum value, X_{max}: maximum value, C_V: coefficient of variation. Groups with identical capital letters in a column indicate that there is no statistical difference ($p < 0.05$) between the samples according to Duncan's multiple range test.

The compression strength values significantly decreased when the MC increased. This result was attributed to swelling of the wood and decreasing of the cell wall ratio in the unit area and of the cohesive forces among the cellulose microfibrils. Significant differences between group averages for the compression strength values were determined individually by Duncan’s multiple comparison tests. The results of Duncan’s grouping are shown in Table 4 by letters. All groups except for the 12% and 16% EMCs showed statistically significant differences ($p < 0.05$) in their compression strengths from each other.

The average air-dry compression strength of the oak wood was 45.5 MPa. The compression strength at 8% MC was 33.0% greater compared to the air-dry compression strength. The compression strengths of the groups at 16%, 20%, and above-FSP MCs were 4.0%, 19.1%, and 50.1% lower than that of the air-dry MC group, respectively.

The compression strength decreased 62.5% as the MC increased from 8% to above the FSP. The changing rate of the oak wood compression strength induced by 1% MC was calculated as 3.1%. It was the greatest changing rate among the mechanical properties measured in this study. Similarly, the greatest changing rate found by Güntekin and Aydın (2013) in Turkish red pine was of the compression strength, at 2.3%.

CONCLUSIONS

1. In the micro-size oak wood samples, the effect of MC was statistically significant for all the measured mechanical properties. All groups except for the 12% and 16% EMCs showed statistically significant differences ($p < 0.05$) in their MOE, tension, and compression strengths from each other. For the bending strength all groups showed statistically significant differences ($p < 0.05$).
2. The bending strength, MOE in bending, tension strength, and compression strength values decreased with increasing MC except for the 16% and 20% EMCs in tension strength.
3. The greatest decrease was observed for the compression strength, while the lowest decrease was observed for the tensile strength, when the MC increased.
4. The changing rates induced by 1% MC were calculated as 3% for the bending strength, 2.5% for the MOE, 2.0% for the tensile strength, and 3.1% for the compression strength.

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