MICRO-MECHANICAL PROPERTIES OF OAK WOOD AND COMPARISON WITH STANDARD-SIZED SAMPLES

Ümit Büyüksarı[1,♠], Nusret As[2], Türker Dündar[2], Ogün Korkmaz[1]

ABSTRACT

The aim of this study was to investigate micro-mechanical properties of Oak (*Quercus petraea*) wood and to compare with standard-size test specimens values. Bending strength, modulus of elasticity in bending, compression strength and tensile strength were determined using micro- and standard-size mechanical test samples. In the micro- and standard size samples, bending strengths were evaluated as 71,2 MPa and 99,4 MPa, modulus of elasticity in bending as 2741,3 MPa and 11394,1 MPa tensile strengths as 98,7 MPa and 93,8 MPa and compression strengths as 45,4 MPa and 46,6 MPa respectively. The results showed that the bending strength, modulus of elasticity and compression strength of the micro-size samples were lower compared to the standard-size samples, while the tensile strength was higher in the micro-size samples. The compression strength values of micro- and standard-size samples were not significantly different. The regression analyses indicated a positive linear regression between the mechanical properties of micro- and standard-size samples. Micro-size specimens can be used to estimate the mechanical properties of Oak wood when obtaining standard-size specimens is not possible.

Keywords: Mechanical properties, micro-size test, *Quercus petraea*, standard-size test, wood quality.

INTRODUCTION

Structural-size with defects and small-size clear samples (standard-size) have been used to determine the mechanical properties of wood. In recent years, micros-sized samples have been used to evaluate the mechanical properties of earlywood and latewood sections, wood strands, and fibers (Jeong 2008, Jeong *et al.* 2009, Groom *et al.* 2002, Mott *et al.* 2002, Wu *et al.* 2005, Kretschmann *et al.* 2006, Hindman and Lee 2007, Deomano and Zink-Sharp 2004, Buyuksari *et al.* 2016).

When obtaining standard-size test samples is not possible, micro-size samples can be used to determine the mechanical properties of wood in structural areas such as wooden bridge, historic buildings etc. Micro-size test samples of structural wood material can be taken periodically and their mechanical properties determined. Thus, changes in the mechanical properties of the wood over time could be observed. This information can provide a solid base for true assessment of the necessity of wooden structure renewal (Buyuksari *et al.* 2016).

[1]Department of Wood Mechanics and Technology, Faculty of Forestry, Duzce University, Duzce, Turkey.

[2]Department of Wood Mechanics and Technology, Faculty of Forestry, Istanbul University, Istanbul, Turkey.

♠Corresponding author: umitbuyuksari@duzce.edu.tr

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There is no standard about the 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. This situation obstructed comparison the results of previous studies (Jeong 2008). The flexural properties of red oak, white oak, and sweetgum (*Liquidambar styraciflua*) flakes dried at 20, 150, and 350 °C were investigated by Plagemann (1982). The size of the specimens was 0,5 × 3,8 × 14,2 mm and loading rate was 0,029 mm/min. Hindman and Lee (2007) measured the bending and tensile properties of both earlywood and latewood sections of loblolly pine (*Pinus taeda*) strands. Dimensions used were 33 × 11 × 0,68 mm in the bending test and 60 × 0,66 × 4,58 mm for earlywood, and 60 × 0,66 × 3,3 mm for latewood in the tension test. The loading rate was selected as 0,127 mm/min. Deomano and Zink-Sharp (2004) investigated the bending properties of wood flakes. The size of the specimens was 25 × 5 × 0,6 mm and loading rate was 2,54 mm/min.

The tensile strength of micro-size wood samples has been investigated by several researchers (Price 1976, Hindman and Lee 2007, Jeong *et al.* 2008, Cai *et al.* 2007, Hunt *et al.* 1989). The tensile properties of willow (*Salix spp.*), yellow poplar (*Liriodendron tulipifera*), red oak (*Quercus spp.*), and loblolly pine (*Pinus taeda*) wood strands were investigated by Cai *et al.* (2007). Hunt *et al.* (1989) conducted tensile testing to determine the tensile strength and tensile modulus of yellow poplar strands with a 2224 N load cell at a test speed of 1,9 mm/min. The compression strength of micro-size wood samples was investigated by Zink-Sharp and Price (2006). They determined the compression strength of sweetgum, yellow poplar, and red maple (*Acer rubrum*) wood species using 1 × 1 × 4 mm specimens. The test was conducted with a loading speed of 0,029 mm/min. The effect of several factors such as gage length, strand thickness, loading rates, and geometry (rectangle-shape and dog-bone shape) on the tensile properties of micro-size samples has been investigated by several researchers (Price 1976, Jeong *et al.* 2008, Kohan *et al.* 2012, Buyuksari 2017).

The mechanical properties of specimens are dependent on the specimen dimensions. This phenomenon is called size effect (Weibull 1951). According to theory of the size effect (weakest link theory) the strength is dependent on the size of 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 member of large volume than in a member of small volume. This region of low strength is assumed to cause complete failure of the member (Weibull 1951).

The analysis of the influencing factors on the size effect of strength and elastic properties is very complex and a number of hypotheses have been developed in the last 100 years. To simplify the matter, it is helpful to look at different species and the different mechanical tests separately (Schotzhauer *et al.* 2015). Madsen and Buchanan (1986) also stated that the size effect is dependent on wood species.

There is limited information about the comparison of mechanical properties of micro- and standard-size samples. Moreover, in most previous studies, authors have compared their findings for micro-size samples with the published values for the standard-size samples in the Wood Handbook (Cai *et al.* 2007, Deomano 2001, Zink-Sharp and Price 2006). Zink-Sharp and Price (2006) stated that the comparison of experimentally determined values with standard handbook values was often useful, although not all-encompassing. Cai *et al.* (2007) found that for willow, yellow poplar, red oak and loblolly pine strands, the tensile strength was, respectively, 31,1; 44,2; 36,2 and 73,4 % lower than that of standard-size samples. Deomano (2001) reported 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. This approach of comparing the values obtained from different trees is not valid for obtaining information about the presence of a correlation between micro- and standard-size samples. It is recognized that tree age and growth conditions such as climate, soil characteristics, slope and altitude affect annual ring width and the mechanical properties of wood. In our previous study (Buyuksari *et al.* 2016), we investigated flexural properties (bending strength and modulus of elasticity) of Scots pine wood (*Pinus sylvestris*) using micro- and standard-size test specimens. The results indicated that a positive linear regression between the flexural properties of the micro- and standard-size specimens. We concluded that the micro-size specimens can be used to estimate the flexural properties of Scots pine wood when obtaining standard-size specimens is not possible. This paper aims to evaluate the mechanical properties of Oak wood (*Quercus petraea*) using micro-size samples and to compare with standard-size samples.

MATERIALS AND METHODS

Materials

Quercus petraea Lieb., commonly known as the sessile oak, Cornish oak or durmast oak, is a species of oak tree native to most of Europe and into Anatolia and Iran. It is used extensively for both interior and exterior building applications throughout Europe. Sample trees were harvested from the Duzce Forest Enterprises in the northwestern part of Turkey. Six trees having straight stems were selected as 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. Micro- and standard-size test samples were prepared from lumber cut from these logs.

Table 1. Properties of the sample trees and sampling area.

Tree species	Tree no.	Diameter of tree at 1,30 m (cm)	Tree age (year)	Altitude (m)	Direction	Slope (%)
Oak	1	34	203	670	East	60
	2	39	207			
	3	38	138			
	4	40	193			
	5	41	214			
	6	40	204			

The cutting plan of the test samples is shown in Figure 1. All specimens were conditioned in a climate chamber at a temperature of 20 ºC and a relative humidity of 65 % for three weeks to target moisture content of 12 % before testing.
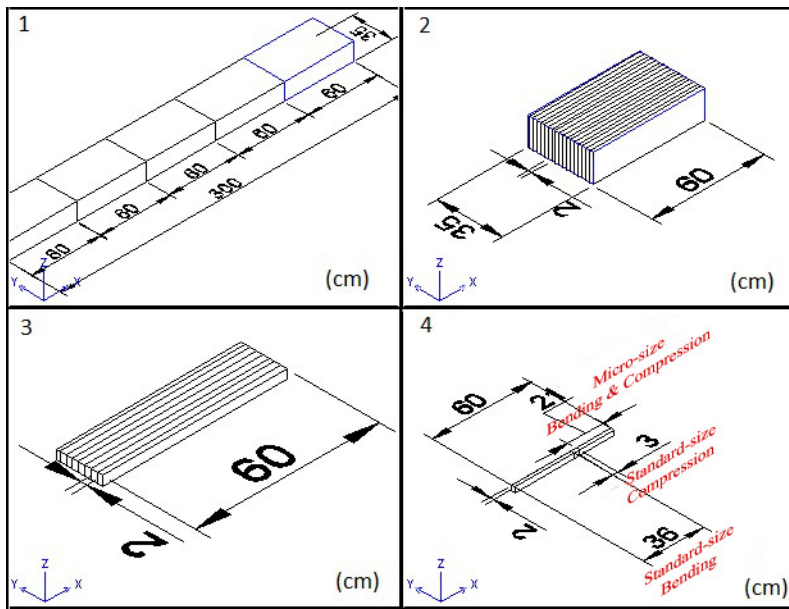
(a)
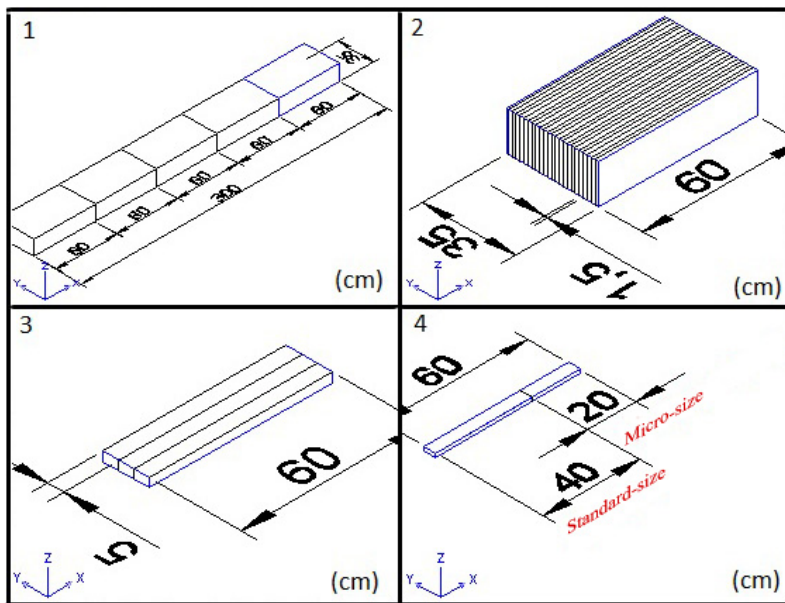
(b)

Figure 1. (a) Cutting plan of bending and compression test samples at standard- and micro-size and (b) tension test samples at standard- and micro-size.

Methods

Standard-size test specimens were cut according to International Organization for Standardization (ISO) in order to determine the bending strength (ISO 13061-3 2014), modulus of elasticity in bending (ISO 13061-4 2014), tensile strength parallel to grain (ISO 13061-6 2014) and compression strength parallel to grain (ISO/DIS 13061-17 2014). The standard-size test samples

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were prepared with dimensions of 20 mm × 20 mm × 360 mm for bending, 15 mm × 50 mm × 400 mm for tension, and 20 mm × 20 mm × 30 mm for compression. In the three-point bending test, load was applied in the direction tangential to the annual rings, and the span/thickness ratio was 15. A Lloyd universal test machine with a 10 kN load cell was used for the standard-size tests.

The same standards were used as a guide for the micro-size tests. The micro-size bending test samples were approximately 50 × 5 × 1-1,3 mm. The tests were performed with a three-point bending fixture. The same span/thickness ratio was used for both the micro-and standard-size bending tests. The micro- and standard-size bending test sample and test setup is shown in Figure 2.

(a)   (b)
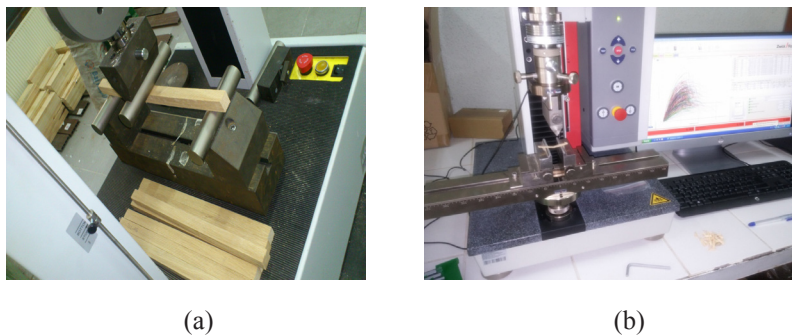
Figure 2. Standard-size bending test sample and test setup (a) and micro-size bending test sample and test setup (b).

Micro-size tension test specimens were approximately 50 × 5 × 1,3 mm and the width of the sample was reduced to 0,8 mm with a sanding drum. The micro-size tensile test specimens and the preparation process are shown in Figure 3.
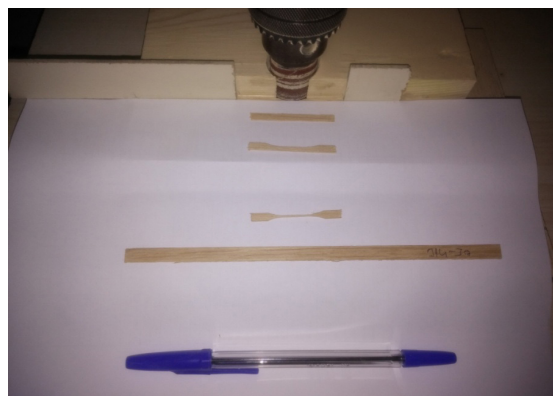
Figure 3. Micro-size tensile test specimens and preparation process.

The gauge lengths were 3 mm for the micro-size tension samples and 280 mm for the standard-size samples. Micro-size compression test specimens had dimensions of 3 × 3 × 5 mm. Micro-size tests were performed with a Zwick universal test machine using a 100 N load cell for bending and compression tests and a 1kN load cell for tension tests. The testing speeds of the bending, tensile and compression tests for the micro-size samples were 1,2; 0,3; and 0,7 mm/min, respectively. The micro-

and standard-size bending, tension, and compression test samples are shown in Figure 4.

Figure 4. The micro- and standard-size test samples for bending (upper) tension (middle), and compression (bottom).

Data analyses and statistical methods

For the MOR, MOE, tensile and compression strength, all multiple comparisons were first subjected to an analysis of variance (ANOVA) at $p < 0,05$ considering two factors (sample size and tree number) and interactions. Post-hoc comparisons were conducted using Duncan's multiple range test. Regression analysis was used to determine the relationship between standard- and micro-size samples.

RESULTS

Table 2 shows the average MOR and MOE values and Duncan test results of the standard- and micro-size Oak wood. In individual trees, the MOR values of the micro-size samples ranged from 61,7 MPa (tree 6) to 76,4 MPa (tree 2 and 3), and in the standard-size samples, from 87,4 MPa (tree 5) to 113,6 MPa (tree 3). Similar trends were observed for micro- and standard-size samples. The highest MOR values were observed for tree 3 in both the micro- and standard-size samples. The average MOR values of micro- and standard-size samples were found to be 71,2 MPa and 99,4 MPa respectively.

Table 2. The average MOR and MOE values and Duncan test results of standard- and micro-size Oak wood samples.

| Tree No | Bending strength (MPa) | | | | | | Modulus of elasticity (MPa) | | | | | |
| | Standard-size | | | Micro-size | | | Standard-size | | | Micro-size | | |
	N	Mean	Std. Deviation	N	Mean	Std. Deviation	N	Mean	Std. Deviation	N	Mean	Std. Deviation
1	67	96,9[bc]	19,0	63	70,6[b]	19,9	67	11553,7[b]	2638,1	63	2604,9[bc]	816,5
2	77	101,2[c]	16,1	74	76,4[b]	18,4	76	11715,1[bc]	2209,3	74	2984,7[d]	820,3
3	110	113,6[d]	14,2	101	76,4[b]	14,6	110	12532,1[c]	2123,9	101	2984,9[d]	683,9
4	44	91,6[ab]	16,7	46	71,9[b]	15,9	44	10859,0[ab]	2437,2	46	2833,7[cd]	762,7
5	50	87,4[a]	14,8	48	63,0[a]	14,5	50	10114,9[a]	2390,6	48	2488,5[ab]	643,6
6	52	87,8[a]	14,2	53	61,7[a]	12,1	52	9994,4[a]	2237,9	53	2248,3[a]	418,4
Total	**400**	**99,4**	**18,6**	**385**	**71,2**	**17,1**	**399**	**11394,1**	**2484,3**	**385**	**2741,3**	**756,7**

In individual trees, the MOE values of the standard-size samples ranged from 9994,4 MPa (tree 6) to 12532,1 MPa (tree 3), and in the micro-size samples, from 2248,3 MPa (tree 6) to 2984,9 MPa (tree 3). The highest and lowest MOE values were observed for tree 3 and 6 in both the micro- and standard-size samples, respectively. The average MOE values of micro- and standard-size samples were determined as 2883,9 MPa and 11394,1 MPa respectively.

The average tensile and compression strength values and Duncan test results of the standard- and micro-size Oak wood samples are shown in Table 3.

Table 3. The average tensile and compression strength values and Duncan test results of standard- and micro-size Oak wood.

| Tree No | Tensile strength (MPa) | | | | | | Compression strength (MPa) | | | | | |
| | Standard-size | | | Micro-size | | | Standard-size | | | Micro-size | | |
	N	Mean	Std. Deviation	N	Mean	Std. Deviation	N	Mean	Std. Deviation	N	Mean	Std. Deviation
1	68	91,5[b]	27,8	64	99,8[bc]	36,2	80	46,3[cd]	6,8	78	44,8[a]	9,6
2	42	96,4[b]	23,2	41	108,6[c]	42,6	61	48,2[d]	8,1	61	44,9[a]	9,2
3	76	113,4[c]	28,8	75	106,8[c]	34,9	88	52,1[e]	6,5	86	49,2[b]	7,2
4	21	78,4[a]	21,2	19	90,1[ab]	37,3	47	42,0[a]	6,5	43	44,9[a]	9,1
5	53	88,9[ab]	28,3	50	97,5[bc]	33,8	59	44,6[bc]	7,8	59	45,1[a]	9,3
6	48	77,2[a]	27,9	44	78,8[a]	22,0	63	43,3[ab]	7,1	61	42,2[a]	9,6
Total	**309**	**93,8**	**30,0**	**293**	**98,7**	**35,8**	**398**	**46,6**	**7,9**	**388**	**45,4**	**9,2**

For individual trees, the tensile strength values ranged from 78,8 MPa (tree 6) to 108,6 MPa (tree 2) in the micro-size samples and from 77,2 MPa (tree 6) to 113,4 MPa (tree 3) in the standard-size samples. The lowest tensile strength values were observed for tree 6 in both the micro- and standard-size samples. The average tensile strength values of micro- and standard-size samples were determined as 98,7 MPa and 93,8 MPa respectively. The results showed that the tensile strength value of the micro-size samples was 5,2 % higher compared to the standard-size samples.

For individual trees, the compression strength values ranged from 42,2 MPa (tree 6) to 49,2 MPa (tree 3) in the micro-size samples and from 42 MPa (tree 4) to 52,1 MPa (tree 3) in the standard-size samples. The highest compression strength values were observed for tree 3 in both the micro- and standard-size samples. The average compression strength values of micro- and standard-size samples were found to be 45,4 MPa and 46,6 MPa, respectively. The results of the present study showed that the compression strength value of the micro-size samples was 2,6 % lower compared to the standard-size samples.

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The factors of the sample size (standard and micro), the number of trees (six different) and their interactions on the MOR, MOE, tensile and compression strength are shown in Table 4.

Table 4. The interactions of sample size and tree number on bending strength, modulus of elasticity, tensile strength and compression strength (ANOVA).

| Source		Type III sum of squares	df	Mean square	F	P
Bending strength	Sample size	125839,5	1	125839,5	491,3	0,000
	Tree number	44945,0	5	8989,0	35,1	0,000
	Sample size*tree number	6891,3	5	1378,3	5,4	0,000
Modulus of elasticity	Sample size	12823042919,8	1	12823042919,8	4304,2	0,000
	Tree number	268350948,8	5	53670189,8	18,0	0,000
	Sample size*tree number	101378910,4	5	20275782,1	6,81	0,000
Tension strength	Sample size	5188,8	1	5188,8	5,3	0,021
	Tree number	71102,8	5	14220,6	14,6	0,000
	Sample size*tree number	7966,4	5	1593,3	1,6	0,147
Compression strength	Sample size	152,3	1	152,3	2,3	0,127
	Tree number	5900,9	5	1180,2	18,1	0,000
	Sample size*tree number	726,1	5	145,2	2,2	0,050

Statistical comparisons of the entire data set were made with regard to the main effects of sample size and tree number. For the MOR and MOE, all factors were significantly different ($p < 0,000$). The tension strength, sample size, and tree number were significantly different ($p < 0,000$), while the interaction of sample size*tree number was not ($p = 0,147$). The compression strength values of micro- and standard size samples were not significantly different ($p = 0,127$).

Regression analysis graphics for the MOR, MOE, tensile strength and compression strength of the micro- and standard-size wood samples are shown in Figures 5, 6, 7 and 8, respectively. The regression analyses indicated that all mechanical properties of the micro-size samples were significantly correlated with the standard samples. The correlation between MOR, MOE, tensile, and compression strength values of the standard- and micro-size samples showed a positive linear relation, correlation coefficients being 0,757; 0,750; 0,717 and 0,758 respectively.
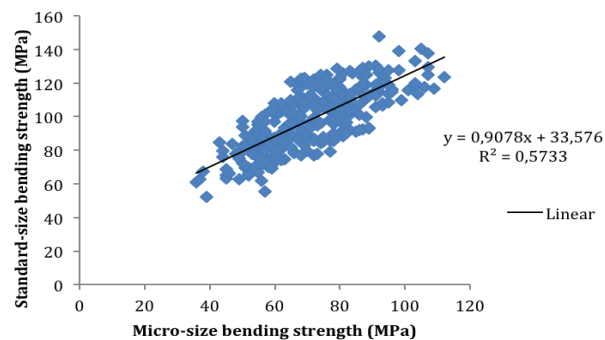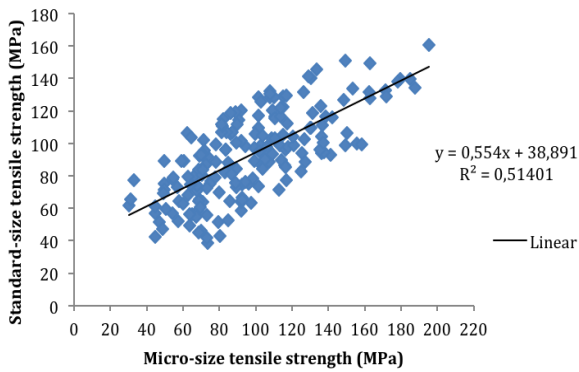

Figure 5. Regression analysis results for bending strength of the micro-size and standard-size wood samples.
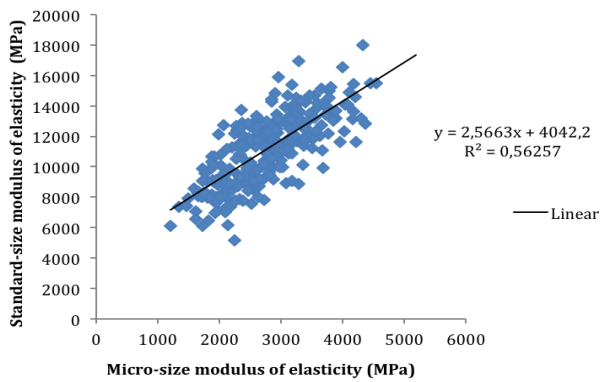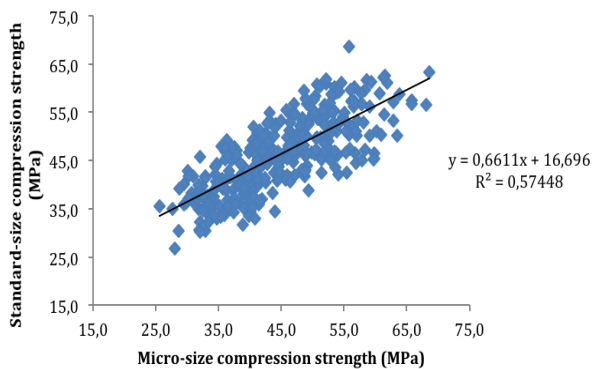
Figure 6. Regression analysis results for modulus of elasticity of the micro-size and standard-size wood samples.

Figure 7. Regression analysis results for tensile strength of micro-size and standard-size wood samples.

Figure 8. Regression analysis results for compression strength of the micro and standard wood samples.

DISCUSSION

In previous studies, researchers determined the MOR values of different wood species using micro-size samples. Deomano and Zink-Sharp (2004) reported that the MOR values of micro-size southern pine, sweet gum, and yellow poplar were 66 MPa, 78,6 MPa, and 89 MPa, respectively. Plagemann (1982) determined that the MOR of white oak and red oak were 91 MPa and 102 MPa, respectively. In this current study, lower MOR value for white Oak wood was determined compared to Plagemann (1982) results. This could be attributed to the dimensions of the specimens, the loading speed, the ratio of earlywood and latewood and span/thickness ratio. Deomano and Zink-Sharp (2004) showed that the MOR and MOE values of wood flakes differed between and within the species. Jeong (2008) pointed out that the results of previous studies are not directly comparable because of different loading conditions and different wood species.

The MOR value of the standard-size samples was 39,6 % higher compared to the micro-size samples. Similar results were found by Buyuksari *et al.* (2016) for scots pine wood and by Deomano (2001) for southern yellow pine and sweet gum. Buyuksari *et al.* (2016) found that the MOR values of the micro-size specimens were 14,3% lower than those of the standard–size specimens. This is contradictory to Weibull's theory, which states that with increasing volume-to-strength decreases (Weibull 1951). Schneeweiß (1964) concluded that the volume strength dependence is a function of absolute specimen volume. He established three different categories. At volumes below 10 cm³ (Category 1) and above 1000 cm³ (Category 3), Weibull's theory applies. In between (Category 2), the volume is considered an influencing factor of low importance. In that current study, the volumes of the micro- and standard-size samples were 0,25 cm³ and 152 cm³, respectively. In a previous study, Deomano and Zink-Sharp (2004) observed lower values in micro-size samples compared to standard-size samples. They compared their findings for micro-size samples with the published values in the Wood Handbook (Green *et al.* 1999) for standard specimens. They found that the MOR values of the standard specimens were higher by 25 % for southern yellow pine and 8,9 % for sweetgum, while they were lower by 27,1 % for yellow poplar. Zink-Sharp and Price (2006) pointed out that comparison of experimentally determined values with standard handbook values was often useful, but not all-encompassing. This current study provides more effective comparison than previous studies because of using wood samples from the same trees.

In previous studies, researchers determined the MOE values of different wood species using micro-size samples. Deomano and Zink-Sharp (2004) found that the MOE of southern pine, sweet gum, and yellow poplar were 4086,9; 4430,6 and 5829,4 MPa, respectively. Plagemann (1982) determined that the MOE values of white oak, red oak and sweetgum in micro-size samples were 4068, 4799 and 5281 MPa. In this current study, lower MOE value for white Oak wood was determined compared to previous studies results. This could be attributed to the dimensions of the specimens (especially thickness of specimens), the loading speed and span/thickness ratio. Plagemann (1982) used samples with 0,5 × 3,8 × 14,2 mm and applied loading rate of 0,029 mm/min. In this current study, samples dimensions were 1-1,3 × 5 × 50 mm dimensions and the loading rate was 1,2 mm/min.

The MOE value of the micro-size samples was 74,7 % lower compared to the standard-size samples. Similar lower MOE values were observed for different wood species in micro-size samples by Deomano and Zink-Sharp (2004) and by Buyuksari *et al.* (2016). Deomano and Zink-Sharp (2004) found that the MOE values of micro-size specimens were lower by 66,9% for southern yellow pine 60,8% for sweetgum and 46,5% for yellow poplar. Buyuksari *et al.* (2016) found that the MOE values of the micro-size scots pine wood specimens were 70,9% lower than those of the standard–size specimens.

Cai *et al.* (2007) found that the tensile strength of red oak wood strands was 40,7 MPa. The tensile strength value of the micro-size samples was 5,2% higher compared to the standard-size samples. In previous studies, it was stated 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 solid wood. When compared to the tensile strength of solid wood (Green *et al.* 1999), those of wood strands from willow, yellow poplar, red oak, and loblolly pine were lower by 31,1; 44,2; 36,2 and 73,4 % respectively. They compared their findings with published values in Wood Handbook (Green *et al.* 1999) for the same wood species. This approach of comparing the values obtained from different trees is not valid for obtaining information about the presence of a correlation between micro-size and standard-size samples. It is recognized that tree age and growth conditions such as climate, soil characteristics, slope and altitude affect annual ring width and the mechanical properties of wood. Also, gage length, sample thickness, loading rate and sample shape (dog- bone or rectangle shape) affect tensile strength of micro-size samples. In this current study, we used dog-bone shape samples unlike Price (1976) and Cai *et al.* (2007). Kohan *et al.* (2012) concluded that dog-bone shape samples had 16 and 27 % higher tensile strength and modulus of elasticity, respectively, than the rectangle-shape samples. The higher tensile strength value in the micro samples could be attributed to the dimensions of the specimens, the loading speed, the ratio of earlywood and latewood and the gage length. For defect-free specimens, Schneeweiß and Felber (2013) mention a strong decrease in tensile strength when increasing the length of the specimens. Jeong (2008) pointed out that the results of previous studies are not directly comparable because of different loading conditions and different wood species. In that study, he indicated that the tensile strength of micro-scale pine wood samples reported by Hindman and Lee (2007) was 36 % higher compared to the work of Cai *et al.* (2007). This comparison clearly shows the effect of sample dimensions and loading rate on the strength properties of micro-size samples. Price (1976) concluded that tensile strength increased as gage length increased. Jeong *et al.* (2008) determined that the thickness of sample wood strands significantly affected the tensile strength of southern pine.

The compression strength value of the micro-size samples was 2,6 % lower compared to the standard-size samples. Similar results were seen by Zink-Sharp and Price (2006) in sweetgum, yellow poplar, and red maple wood. Zink-Sharp and Price (2006) observed that compression strength values of micro-size sweetgum, yellow poplar, and red maple wood were 39,2; 33,5 and 41,6 MPa respectively. They found that the compression strength of the micro-size samples was close to but lower than handbook values for these wood species. They explained that the exact cause of this difference was unknown, but that there were at least two probable explanations. A size effect was one possibility and the second was that damage created by specimen preparation had a more significant impact on the intra-ring specimens than on the standard specimens. Schneeweiß (1964) stated that the compression strength of Spruce wood firstly decreased with increasing specimen volume then increased slightly to maximum and finally decreased again. Schlotzhauer *et al.* (2015) observed that the compression strength increased as specimen volume increased in Beech, Oak and Lime wood while the specimen dimensions did not influence the compression strength of maple, birch and ash wood. Madsen and Buchanan (1986) stated that the size effect is dependent on wood species.

CONCLUSIONS

From this study, the following conclusions can be drawn:

The bending strength, modulus of elasticity and compression strength of the micro-size samples were lower compared to the standard-size samples, while tensile strength was higher in micro-size samples.

The effects of sample size, individual trees and the interactions between size and trees on bending strength, modulus of elasticity and tensile and compression strength were statistically significant, except for the effect of the interaction of sample size and individual trees on tensile strength and sample size on compression strength.

The regression analyses indicated that all mechanical properties of the micro-size samples were significantly correlated with the standard-size samples. A positive linear regression between the micro- and standard-size samples was shown for all measured mechanical properties.

Micro-size test samples can be used to estimate the standard-size test results for all measured properties of Oak wood.

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