Effect of Loading Rate on Mechanical Properties of Micro-size Scots Pine Wood

Ümit Büyüksarı

The use of micro-size samples is becoming more important to determine the mechanical properties of wood. The aim of this study was to investigate the effect of the loading rate on the micro-mechanical properties of Scots pine (*Pinus sylvestris* L.) wood. The bending strength, modulus of elasticity in bending, compression strength parallel to the grain, and tensile strength parallel to the grain were determined using micro-size test samples. Three different loading rates were used for each test. The first loading rates were determined according to related ISO standards, and the second and third loading rates were determined as half- and quarter- of the standard loading rates. The results showed that the loading rate had significantly affected the modulus of elasticity and compression strength of Scots pine wood. However, the loading rate had no significant effect on the bending and tensile strength of the Scots pine wood. When the loading rate decreased, the mechanical properties of micro-size Scots pine wood were decreased.

Keywords: Micro-size specimens; Loading rate; Scots pine; Mechanical properties

Contact information: Department of Wood Mechanics and Technology, Duzce University, Duzce, Turkey; Email: umitbuyuksari@duzce.edu.tr

INTRODUCTION

The micro-scale level is defined as the range of 1×10^{-3} to 1×10^{-6} m, and this range has been the focus of research concerning the wood cell wall and earlywood and latewood fibers (Jeong 2008). The use of micro-sized samples is gaining importance in determining the mechanical properties of wood. However, there is no standard method for micro-sized test samples. The sample dimensions and loading rates have varied from one article to another. Micro-sized samples have been used to determine the mechanical properties of earlywood and latewood sections, wood strands, and fibers by several researchers (Plagemann *et al.* 1984; Hunt *et al*. 1989; Groom *et al*. 2002; Mott *et al*. 2002; Deomano and Zink-Sharp 2004; Zink-Sharp and Price 2006; Hindman and Lee 2007; Jeong 2008; Jeong *et al*. 2009; Buyuksari *et al*. 2016; Roszyk *et al*. 2016).

In previous studies, researchers have used different loading rates and dimensions. This situation has impeded their comparison with the results of other studies (Jeong 2008). Deomano and Zink-Sharp (2004) determined the modulus of rupture (MOR) and modulus of elasticity (MOE) of southern yellow pine (*Pinus* spp.), sweet gum (*Liquidambar styraciflua* L.), and yellow poplar (*Liriodendron tulipifera* L.) wood flakes using micro-size samples. A 2.54 mm/min loading rate was applied for the tests. In another study, Hindman and Lee (2007) performed the bending and tensile tests for both the earlywood and latewood sections of loblolly pine (*Pinus taeda*) strands. The loading rate for the tensile test was 0.127 mm/min. Plagemann *et al.* (1984) investigated the bending properties of red oak, white oak, and sweetgum flakes, and the applied loading rate was 0.029 mm/min. Hunt *et al*. (1989) conducted tensile testing to determine the tensile strength and tensile modulus of yellow poplar (*Liriodendron tulipifera* L.) strands at a loading rate of 1.9 mm/min. Zink-Sharp and Price (2006) conducted the compression test with a loading speed of 0.029 mm/min. Buyuksari *et al*. (2016) investigated the flexural properties of scots pine wood using both micro- and standard-size samples. They found that the bending strength and modulus of elasticity of the micro-size specimens were lower compared to those of the standard-size specimens. The effects of the specimen size and the individual trees, and the interactions between the size and the trees, on the bending strength and modulus of elasticity were found to be statistically significant, and a positive linear regression was observed between the flexural properties of the micro- and standard-size specimens. They concluded that the micro-size test specimens can be used to estimate the standard-size test results for the flexural properties of Scots pine wood.

Several researchers have investigated the effect of several factors on the tensile properties of micro-sized samples. Price (1976) examined the effect of the gauge length on the tensile strength and concluded that the tensile strength increased as the gauge length was increased. Jeong *et al*. (2008) studied the effect of strand thickness and loading rates on the tensile strength and tensile modulus of southern pine (*Pinus spp*.) strands. In another study, Kohan *et al*. (2012) investigated the effect of geometry on the tensile strength and tensile modulus of elasticity of wood strands. They compared the tensile strength and modulus of elasticity of rectangular and tapered (dog-bone shaped) wood strands and concluded that the dog-bone shaped samples had 16% and 27% higher tensile strength and modulus of elasticity, respectively, than the rectangular ones. The variation in the mechanical properties was not statistically different for the two shapes.

The wood cell wall is composed of highly organized elastic cellulose fibrils encased in a matrix of amorphous viscoelastic lignin-hemicellulose. This indicates that its elastic and viscous (time-dependent) characteristics determine its mechanical behavior (Lakes 2009). It is well known that the loading rate affects the mechanical properties of solid wood (Gerhards 1977; Gerhards and Link 1986; Spencer 1979), wood-based panels (Gerhards 1977), and wood-plastic composites (Brandt and Fridley 2003). Gerhards (1977) reviewed world literature on the strength-related effects of the loading rate on wood and wood-based materials. He suggested that the effect of the loading rate on strength is most pronounced in tension perpendicular to the grain, followed by compression parallel to the grain, bending, and shear. Wood loaded at a more rapid rate yields greater strength values than that loaded at slower rates. This fact has been attributed to a number of reasons that are mostly based on the theory that failure occurs when a critical strain on the timber has been reached. The failure at lower loads takes place as a consequence of the viscous flow, or creep, enabled by the lower rates of loading (Dinwoodie 2000). Thus, strength can be considered as an exponential function of the loading rate over several orders of magnitude (Green *et al.* 1999). However, there is limited information about the effect of the loading rate on the mechanical properties of wood in micro-sized samples. Jeong *et al*. (2008) evaluated the effects of the loading rate on the tensile properties of southern pine (*Pinus* spp.) strands. They used three different loading rates (0.102 mm/min, 0.254 mm/min, and 0.406 mm/min). They discovered that the tensile modulus of elasticity and the tensile strength from different loading rates were not significantly different. The current study seeks to evaluate the effect of the loading rate on the mechanical properties of micro-sized Scots pine (*Pinus sylvestris* L.) wood.

EXPERIMENTAL

Materials

Eight Scots pine trees with straight stems were harvested from the Bolu Forest Enterprises in the northwestern part of Turkey. Logs of 3 m in length were cut from each tree. Micro-sized test samples were prepared from the lumber cut from these logs. Samples were longitudinally cut into 3 parts, and each of them was used for different loading rates. The preparation process of the micro-sized test specimens is shown in Fig. 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 reach a target moisture content of 12% prior to testing.

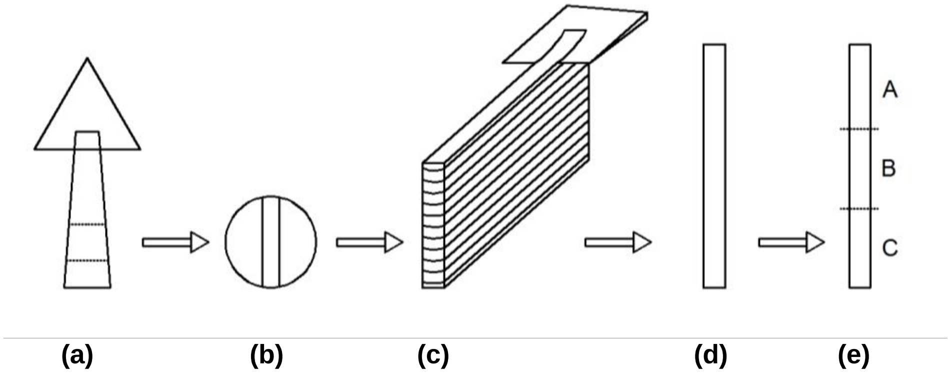

Fig. 1. The preparation process-cutting plan of micro-size test specimens; a) Cutting the logs, b) Cutting the 6-cm-thick planks from logs, c) Cutting the micro-size samples from planks, d) Micro-size samples, and e) Longitudinal cutting for different loading rates

Methods

The micro-size flexural test samples were approximately 50.0 mm (L) × 5.0 mm (R) × 1 mm to 1.3 mm (T). The tests were performed with a three-point bending fixture. The load was applied tangential to the annual rings, and the span/thickness ratio was 15. The micro-size tensile test specimens were approximately 50 mm (L) × 5.0 mm (R) × 1 mm to 1.3 mm (T), and the width of the sample was reduced to 0.8 mm with a sanding drum. The micro-size compression test specimens had dimensions of 3 mm (R) × 3 mm (T) × 5 mm (L). The bending, tensile, and compression test samples are shown in Fig. 2.

Fig. 2. The bending, tensile, and compression test samples. Numbers on the ruler correspond to cm units, and the fine scale markings correspond to mm units.

Three different loading rates were used for each test. The first loading rates (Group A) were determined according to ISO standards ISO 13061-3 (2014), ISO 13061-4 (2014), ISO 13061-6 (2014), and ISO 13061-17 (2014). The second (Group B) and third (Group C) loading rates were selected as half- and quarter- of the standard loading rates. The loading rates for all of the tests are shown in Table 1.

Table 1. Loading Rates for All Test Groups

Group	Loading Rate (mm/min)		
	Compression Test	Tensile Test	Bending Test
A	0.7	0.3	2
B	0.35	0.15	1
C	0.175	0.075	0.5

Data Analyses and Statistical Methods

The SPSS Statistics computer software (IBM Corporation, New York, USA), version 21 was used for the statistical analysis. For the bending strength, modulus of elasticity in bending, tensile, 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

Figure 3 depicts the effect of the loading rate on the bending strength values and Duncan test results of micro-size Scots pine wood. The average bending strength value of the standard loading rate (2 mm/min) was 62.0 MPa. It was observed that the bending strength values of Scots pine wood slowly decreased when the loading rate was decreased. The bending strength values of the half and quarter loading rates were lowered by 2.3% and 4.2% compared to the standard loading rate, respectively (Fig. 7). The effect of the loading rate was not statistically significant for the bending ($p = 0.220$) in the micro-size Scots pine wood samples (Table 2).

There is no information on the effect of the loading rate for the bending strength properties of micro-size wood samples. Green *et al.* (1999) reported that higher strength was achieved in standard and structural-sized wood loaded at a more rapid rate than when loaded at slower rates. Thus, a load of approximately 10% higher than the load obtained in a standard static strength test was required to induce failure in 1 s. However, presently the effect of the loading rate on the bending strength was not statistically significant (Table 2). The size effect, the selected loading rates, and the high variability of the values could be reasons for this result. The size effect according to the weakest link theory states that the strength of a highly stressed material is dependent on the size, based on the fact that a region of low strength will more likely occur in a component of large volume than in one of small volume. Thus, complete failure of the component is assumed to result from this low strength region (Weibull 1951). Both Dinwoodie (2000) and Sugiyama (1967), using lower loading rates (2 days-2 years), determined that, as a result of creep, the mechanical properties of wood were influenced by the loading rate. Lanvermann *et al*. (2014), however, reported that, because of the high local variability of the values, the mechanical properties were not significantly decreased. Moreover, Dinwoodie (2000) concluded that the effect of the loading rate depended on the size of the sample and that the rate was higher in structural timber than in small, clear specimens.

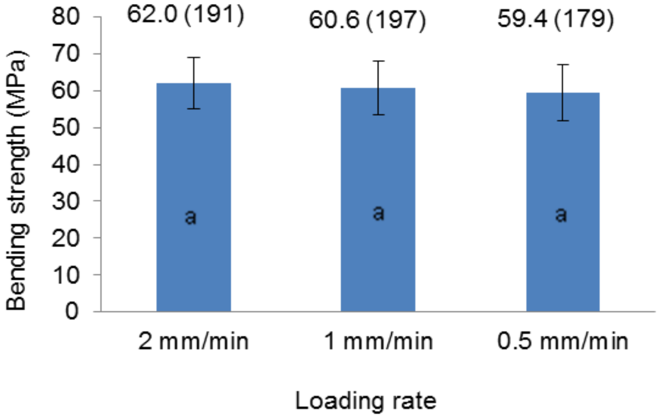

Fig. 3. Bending strength values of micro-size Scots pine wood as a function of loading rate and Duncan test results (The values in the brackets show number of specimens, error bars show the standard deviation values, groups with same letters indicate that there is no statistical difference ($p < 0.05$) between the samples according Duncan's multiply range test)

The effect of the loading rate on the modulus of elasticity values and Duncan test results of micro-size Scots pine wood are shown in Fig. 4. The modulus of elasticity of standard loading rate (2 mm/min) was 2855 MPa. The modulus of elasticity values of Scots pine wood decreased as the loading rate was decreased. The modulus of elasticity values of the half and quarter loading rates were lower by 12.8% and 10.6% compared to the standard loading rate, respectively (Fig. 7). In micro-size Scots pine wood samples, the effect of the loading rate was statistically significant for the modulus of elasticity in bending ($p < 0.0001$) (Table 2). As mentioned above, the increased strength and stiffness values result from an increase in the loading rate (Dinwoodie 2000). Brandt and Fridley (2003) stated that the expected decrease in deflection at failure occurred due to the decreasing effect of material viscous flow with the increased loading rate.

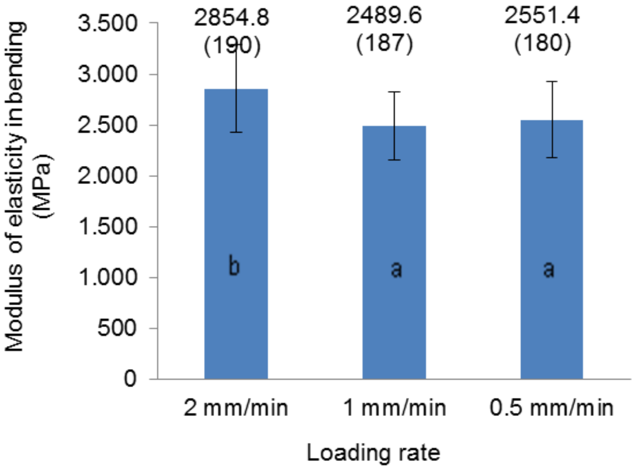

Fig. 4. Modulus of elasticity values of micro-size Scots pine wood as a function of loading rate and Duncan test results (The values in the brackets show number of specimens, error bars show the standard deviation values, groups with same letters indicate that there is no statistical difference ($p < 0.05$) between the samples according Duncan's multiply range test)

Figure 5 indicates the effect of the loading rate on the tensile strength and Duncan test results of micro-size Scots pine wood. The tensile strength of the standard loading rate (0.3 mm/min) was 92.7 MPa. The tensile strength values of Scots pine wood slightly decreased when the loading rate was decreased. The decreases in the tensile strength values were 0.3% and 1.6% for the half and quarter loading rates, respectively (Fig. 7). The effect of the loading rate was not statistically significant for tensile strength ($p = 0.898$) in the micro-size Scots pine wood samples (Table 2). Jeong *et al*. (2008) found that the tensile strength values of the loblolly pine wood strand were 52.2 MPa, 47.2 MPa, and 50.0 MPa for 0.406 mm/min, 0.254 mm/min, and 0.102 mm/min loading rates, respectively.

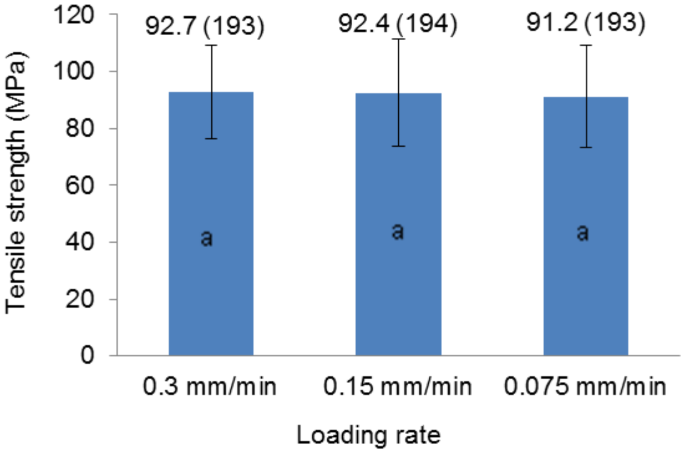

Fig. 5. Tensile strength values of micro-size Scots pine wood as a function of loading rate and Duncan test results (The values in the brackets show number of specimens, error bars show the standard deviation values, groups with same letters indicate that there is no statistical difference ($p < 0.05$) between the samples according Duncan's multiply range test)

Figure 6 shows the effect of the loading rate on the compression strength and Duncan test results of micro-size Scots pine wood. The compression strength of the standard loading rate (0.7 mm/min) was 36.2 MPa. The compression strength values of Scots pine wood slightly increased after then decreased when the loading rate was decreased to the half- and quarter- of the standard loading rate. The compression strength value of the standard loading rate was 5.5% higher for the half loading rate and 1.4% lower for the quarter loading rate, respectively (Fig. 7). In micro-size Scots pine wood samples, the effect of the loading rate was statistically significant for the compression strength ($p < 0.0001$). Liska (1950) examined the effect of rapid loading and found that the maximum crushing strength increased with an increase in the loading rate. Liska (1950) also determined that the maximum crushing strength of Douglas fir wood was 42.5 MPa at a loading rate of 2.2 mm/min, 44.4 MPa at 10 mm/min, 45.0 MPa at 19.6 mm/min, 47.4 MPa at 48.4 mm/min, and 47.1 MPa at 71.1 mm/min. He noted that a tenfold increase in the loading rate resulted in a compression strength increase of approximately 8%. The differences between the current study and the results of Liska (1950) can be attributed to different loading rates and sample size. The compression strength of the micro-sized samples of three different wood species was investigated in one previous study (Zink-Sharp and Price 2006). It was observed that although the compression strength of the micro-sized samples was close to that of the standard-sized samples, it was still lower than the standard (handbook) values for the three wood species. They could not explain the exact cause for this difference. Two of the possible reasons included the size effect and the damage created during the specimen preparation, with a more significant impact being detected on the intra-ring samples than on the standard-sized ones.

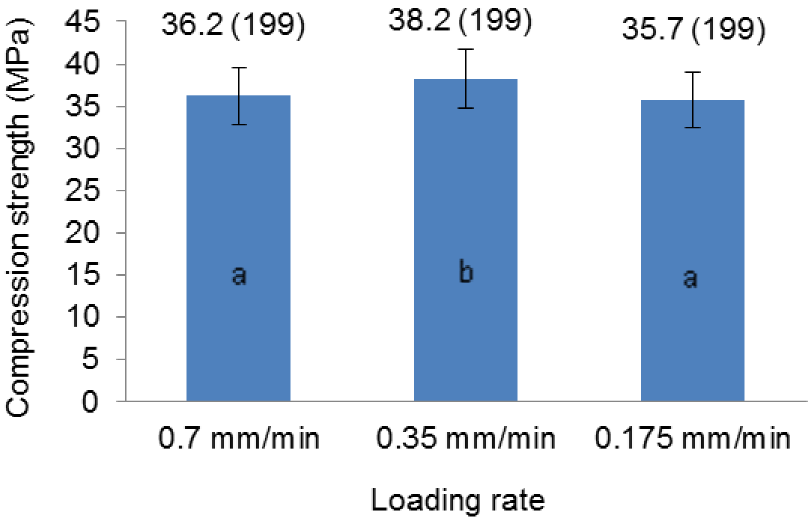

Fig. 6. Compression strength values of micro-size Scots pine wood as a function of loading rate and Duncan test results (The values in the brackets show number of specimens, error bars show the standard deviation values, groups with same letters indicate that there is no statistical difference ($p < 0.05$) between the samples according Duncan's multiply range test)

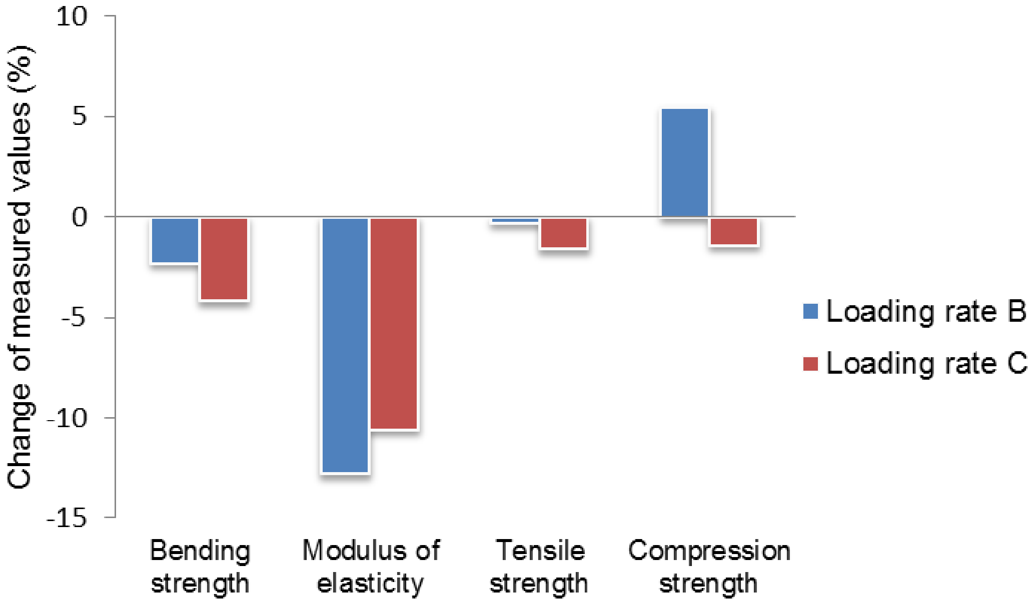

Fig. 7. The changes of the measured strength and stiffness values

Table 2 shows the effect of the loading rate on bending strength, modulus of elasticity in bending, tensile and compression strength of Scots pine wood.

Table 2. Effect of Loading Rate on Bending Strength, Modulus of Elasticity in Bending, Tensile And Compression Strength of Scots Pine Wood (ANOVA)

Test Type	Source	Sum of Squares	df	Mean Square	F-value	Significance
Bending Strength	Between Groups	643.3	2	321.7	1.519	0.220
	Within Groups	119462.5	564	211.8		
	Total	120105.8	566			
Modulus of Elasticity	Between Groups	14394060.3	2	7197030.1	12.279	0.000
	Within Groups	324723069.3	554	586142.7		
	Total	33911712.6	556			
Tension Strength	Between Groups	270.6	2	135.3	0.108	0.898
	Within Groups	725829.5	577	1257.9		
	Total	726100.2	579			
Compression Strength	Between Groups	711.6	2	355.8	7.70	0.000
	Within Groups	27437.6	594	46.2		
	Total	28149.2	596			

CONCLUSIONS

1. In micro-size Scots pine wood samples, the effect of the loading rate was statistically significant for the modulus of elasticity in bending ($p < 0.0001$) and the compression strength ($p < 0.0001$).
2. The effect of the loading rate was not statistically significant for the bending ($p = 0.220$) and tensile strength ($p = 0.898$) in the micro-size Scots pine wood samples.
3. The strength and stiffness (modulus of elasticity) values were generally decreased as the loading rate decreased. The largest decreases were observed for the modulus elasticity values with the values of 12.8% and 10.6%.
4. The largest decrease was observed for the modulus elasticity as the loading rate decreased from 2 mm/min to a 1 mm/min loading rate. Also, a slight increase was observed for the compression strength when the loading rate decreased from 0.70 mm/min to 0.35 mm/min.

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