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INFLUENCE OF MOISTURE CONTENT ON ELASTIC CONSTANTS OF SCOTS PINE WOOD SUBJECTED TO COMPRESSION

Moisture content is the environmental factor that has the greatest influence on the physical and mechanical properties of wood materials. This research aimed to quantify the effect of moisture content on the elastic constants of Scots pine wood grown in Turkey under different humidity regimes. The elastic properties investigated include E_L, E_R, E_T, G_{LR}, G_{LT}, G_{RT}, υ_{LR}, υ_{LT}, υ_{RL}, υ_{RT}, υ_{TL} and υ_{TR} under compression. The compression strength in all principal directions was also studied. Specimens were cut from sapwood of pine logs and sorted into four matched MC groups. Clear wood samples were conditioned at 21°C and 45%, 65%, 85%, 95% RH, and subjected to compression tests. A biaxial extensometer was used to measure active and passive strain during loading. Young's modulus, shear modulus, Poisson's ratios and compression strength were calculated and compared for all orthotropic directions. The results indicate that the elastic and strength properties are significantly different in the principal directions. The Young's modulus, shear modulus and compression strength of the tested samples were strongly affected by moisture content. These properties exhibit a linear decrease with increasing moisture content. Poisson's ratios are not sensitive to MC changes.

Keywords: elastic constants, compression, moisture content, Scots pine

Introduction

Wood is a widely used material, of which the mechanical properties are strongly influenced by surrounding relative humidity. Thus, the mechanical properties of wood are altered by its moisture content (MC) in practical use, particularly in structural applications. MC is accepted as a major strength and stiffness reducing factor [Ross 2010]. Most of the elastic and strength properties of wood decrease with increasing MC below fibre saturation point [Panshin and de Zeeuw 1980].

The susceptibility of mechanical properties to MC changes will vary, with strength properties more sensitive than stiffness properties, and static properties more sensitive than dynamic properties [Dinwoodie 2000]. More detailed

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discussion on this matter can be found in the studies of Gerhards [1982], Green and Kretschmann [1994], Kretschmann and Green [1996], Hering et al. [2012a,b], and Ozyhar et al. [2013]. While the influence of MC on the mechanical behaviour of wood in the L direction is relatively widely investigated [Gerhards 1982], studies on behaviour in the perpendicular directions (R and T) are scarce. Understanding of moisture-dependent anisotropic behaviour of wood species is necessary for advanced computational models, such as the finite element models used in engineering analysis.

The most widely distributed pine species throughout the world, Scots pine (*Pinus sylvestris*), can be found across Eurasia. Scots pine is also one of the most important wood species grown in Turkey, covering approximately 6.8% of total forestland [Büyüksarı et al. 2017]. Mechanical investigations of Turkish wood species are generally concerned with behaviour at a constant MC of 12% in bending. Although data are needed for three-dimensional modelling of moisture dependent mechanical behaviour, only a few references are available for this purpose [Güntekin et al. 2015, 2016a,b].

The purpose of this study was to determine a set of elastic and strength parameters of Scots pine wood in compression tests under different humidity regimes. The parameters evaluated in this study are the Young's modulus, shear modulus, Poisson's ratios, and compression strength in the principal directions.

Materials and methods

Small clear wood specimens were cut from Scots pine (*Pinus sylvestris*) logs harvested from Bolu-Aladaglar Forest District in Turkey. The geographical coordinates of the research area are 40°36'N 31°39'E. Logs were approximately 50 cm in diameter. Ten samples with nominal dimensions of 20 × 20 × 60 mm for each direction (L, R, T), and with a 45° angle in planes LR, LT and RT from the planks, were prepared (fig. 1).

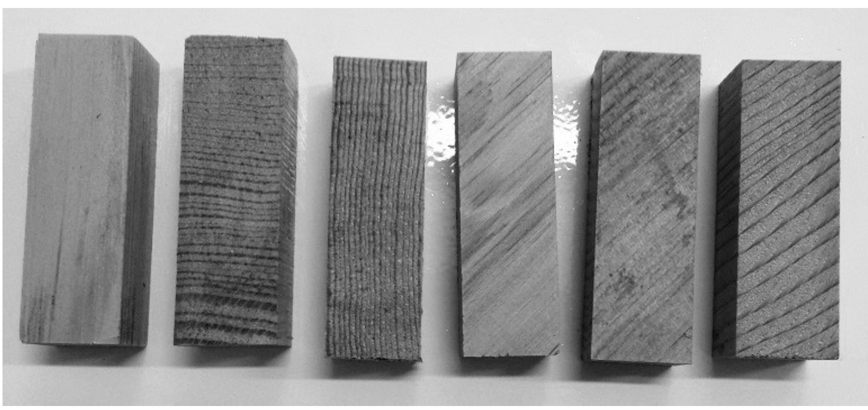

Fig. 1. Specimens used in compression testing

All samples came from sapwood planks cut from the trunk section between 1 and 3 metres from ground level. Before testing, compression specimens were randomly divided into four groups and conditioned in climatic chambers at 45%, 65%, 85% and 95% relative humidity (RH) at a temperature of 21°C. After the specimen reached equilibrium MC, uniaxial compression tests were carried out using a universal testing machine (ELISTA® brand). All tests were performed at standard climatic conditions (65% RH and 21°C). To minimize the influence of the MC change, specimens were tested immediately after removal from the climatic chamber. Wood MC was determined by the oven-drying method. The feed rate was defined in such a way that failure of the specimen should be attained in 90 (±30) s. The strains were measured using a biaxial extensometer (fig. 2).

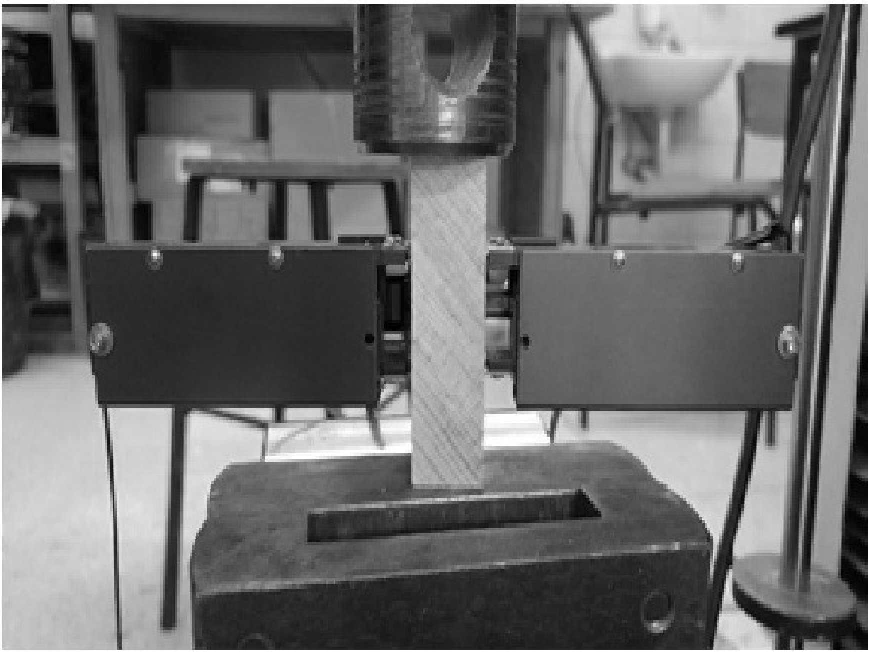

Fig 2. Compression testing using a biaxial extensometer

Apparent densities of the samples were calculated using a stereometric method, based on measurements of the sample volume and mass. The stress-strain curves obtained were used to evaluate the Young's modulus, Poisson's ratios and strength properties of the specimens. The following formulae were applied:

$$E_i = \frac{\Delta \sigma_i}{\Delta \varepsilon_i} = \frac{\sigma_{i,2} - \sigma_{i,1}}{\varepsilon_{i,2} - \varepsilon_{i,1}} \qquad i \in R, L, T \qquad (1)$$

$$\upsilon_{ij} = -\frac{\varepsilon_j}{\varepsilon_i}, \qquad i, j \in R, L, T \text{ and } i \neq j \tag{2}$$

where E_i is the elastic modulus, σ_i is the stress in the linear portion of the stress--strain curve, ε_i is the corresponding strain in the linear portion of the stress--strain curve, υ_{ij} are Poisson's ratios, and the limits of proportionality were derived from the linear portion of the stress-strain curve. The elastic modulus is in the direction of the subscript: L (longitudinal), R (radial) or T (tangential). For the υ ratios, the first subscript is the direction of the load, and the second subscript is the perpendicular direction of measured dimensional change. Since the strength behaviour of wood in the R and T directions is obscure, maximum compression strength (CS) was calculated using 0.2% yield values with the following formula:

$$\sigma_{UCS} = \frac{P_{\max}}{A} \tag{3}$$

where σ_{UCS} represents yield strength, $P_{\max}$ is the yield load and A is the cross-sectional area of the specimen. The shear modulus of the specimens with 45° angle in planes LR, LT and RT was determined using the following:

$$G_{LR} = \frac{\tau_{LR}}{\gamma_{LR}} = \frac{\sigma_V}{2(\varepsilon_H - \varepsilon_V)} \tag{4}$$

$$G_{LT} = \frac{\tau_{LT}}{\gamma_{LT}} = \frac{\sigma_V}{2(\varepsilon_H - \varepsilon_V)} \tag{5}$$

$$G_{RT} = \frac{\tau_{RT}}{\gamma_{RT}} = \frac{\sigma_V}{2(\varepsilon_H - \varepsilon_V)} \tag{6}$$

where σ_V is the average vertical stress, ε_H is the average horizontal strain and ε_V is the average vertical strain. More detailed information on the calculation of shear modulus from angled specimens in compression tests can be found in Aira et al. [2014]. A one-way layout ANOVA analysis was performed in each direction using SAS statistical analysis software to interpret the effect of MC on the measured properties of the clear wood samples.

Results and discussion

An example of the load-deformation curves obtained in the calculation of the properties considered in the study is shown in figure 3.

Average values of density, moisture content, Young's modulus, compression strength and Poisson's ratios of the tested specimens in the principal directions are given in tables 1-3. Shear modulus values determined from compression tests for the LR, LT and RT planes are listed in table 4. The coefficient of variation of Young's modulus values ranged from 12% to 29%, being particularly high in the R direction.

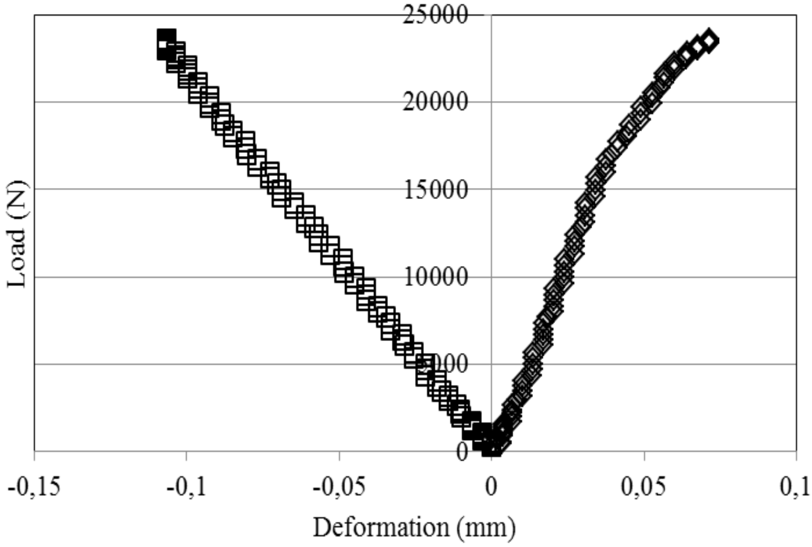

Fig. 3. Average load-deformation curves obtained from compression tests

Table 1. Average values determined in the L direction

Density (g/cm^3)	MC (%)	E_L (N/mm^2)	CS (N/mm^2)	υ_{LR}	υ_{LT}
0.52	8.0	15621 (18)*	56.65 (11)	0.41 (27)	0.69 (14)
0.53	12.5	14998 (14)	45.8 (6)	0.60 (23)	0.74 (23)
0.55	17.4	13058 (27)	37.2 (9)	0.51 (37)	0.69 (30)
0.56	21.6	10230 (25)	29.3 (5)	0.39 (39)	0.60 (19)
0.55[1]	10	16300	–	0.42	0.51
0.505[2]	11.09	10283	–	0.399	0.618
0.505[3]	12	14300	–	0.61	-

[1]Dinwoodie (2000), [2]Aira et al. (2014), [3]Pencik (2015), *Coefficients of variation.

Table 2. Average values determined in the R direction

Density (g/cm^3)	MC (%)	E_R (N/mm^2)	CS (N/mm^2)	υ_{RT}	υ_{RL}
0.53	8.1	804 (24)*	4.37 (14)	0.69 (28)	0.083 (29)
0.54	12.7	763 (29)	3.85 (16)	0.69 (24)	0.075 (37)
0.55	17.0	569 (24)	2.96 (14)	0.63 (36)	0.071 (40)
0.56	20.59	420 (19)	2.46 (10)	0.73 (20)	0.164 (49)
0.55[1]	10	1100	–	0.63	0.038
0.505[2]	11.09	1994	–	1.09	0.107
0.505[3]	12	700	–	0.48	0.030

[1]Dinwoodie (2000), [2]Aira et al. (2014), [3]Pencik (2015), *Coefficients of variation.

Table 3. Average values determined in the T direction

Density (g/cm^3)	MC (%)	E_T (N/mm^2)	CS (N/mm^2)	υ_{TR}	υ_{TL}
0.53	8.1	682 (12)*	8.4 (7)	0.64 (39)	0.057 (34)
0.54	12.1	532 (13)	6.4 (6)	0.68 (16)	0.063 (28)
0.54	17.0	362 (12)	4.83 (7)	0.50 (31)	0.065 (31)
0.57	23.3	283 (18)	4.28 (6)	0.55 (19)	0.084 (38)
0.55[1]	10	570	-	0.68	0.015
0.505[2]	11.09	994	-	0.796	0.068
0.505[3]	12	545	-	0.38	0.04

[1]Dinwoodie (2000), [2]Aira et al. (2014), [3]Pencik (2015), *Coefficients of variation.

Table 4. Average shear values determined in compression tests

Density (g/cm^3)	MC (%)	G_{LR} (N/mm^2)	G_{LT} (N/mm^2)	G_{RT} (N/mm^2)
0.53	8.2	1041 (25)*	911 (19)	108 (24)
0.54	12.2	1007 (15)	903 (27)	107 (30)
0.55	17.7	828 (34)	737 (18)	86 (27)
0.56	22.8	737 (18)	655 (26)	74 (30)
0.55[1]	10	1160	680	66
0.505[2]	11.09	1334	1280	737
0.505[3]	12	1230	800	500

[1]Dinwoodie (2000), [2]Aira et al. (2014), [3]Pencik (2015), *Coefficients of variation.

The ratio of Young's modulus in the L, R and T directions for the Scots pine used in the study is approximately 28:1.4:1, which is somewhat different from the ratio for softwood species reported in the Wood Handbook [Ross 2010], but is similar to the ratios reported by Dinwoodie [2000] and Pencik [2015]. According to Bodig and Jayne [1993] E_L is usually 10 to 20 times higher than E_R, and E_R is double the value of E_T.

The modulus of elasticity values in bending reported for Scots pine wood in the literature vary between 8515 and 19102 N/mm^2 [Verkasalo 1992; Boonstra et al. 2007; Hassan et al. 2013; Kamperidou et al. 2014; Yıldırım et al. 2015; Kaygin et al. 2016] depending upon the growth site conditions and density. While Verkasalo [1992] indicates that the increase in E is mostly due to the increase in the density, Kaygın et al. [2016] claim that elevation is an important factor for the MOE. By comparison with the available literature, the Young's modulus value in the L direction at 65% RH obtained in this study is an average.

The Young's modulus in all principal directions decreases significantly with increasing MC, as expected ($p < 0.05$; $R^2 = 0.92$). With a decrease of 58% over the measured MC range, the decrease is most significant for E_T, followed by E_R (47%) and E_L (34%). The specimens conditioned at 45% and 65% did not produce significantly different Young's modulus values. The Young's modulus in the principal directions exhibits almost linear relationships with moisture content (fig. 4).

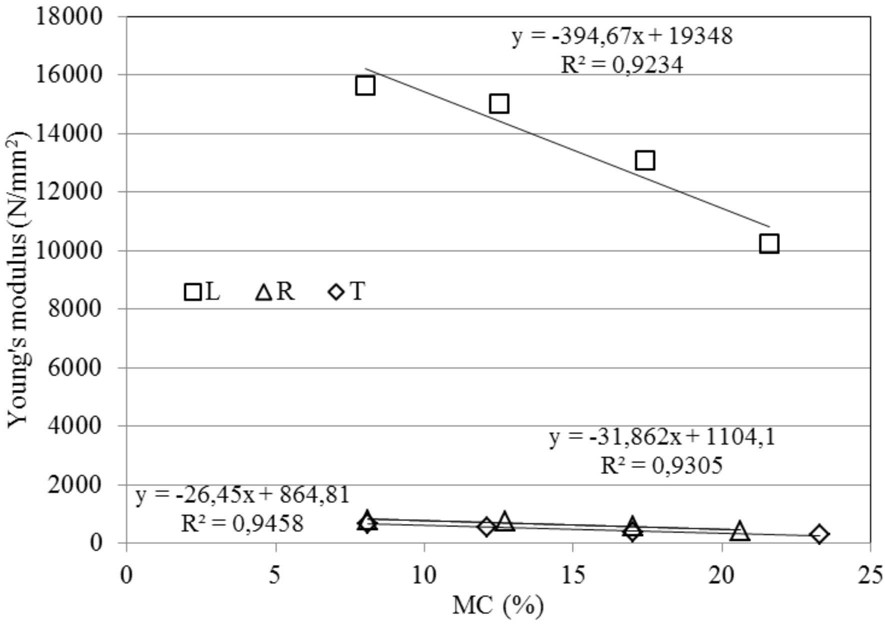

Fig 4. Effect of MC on Young's modulus

The shear modulus values determined from the compression tests follow the well-known ordering $G_{LR} > G_{LT} > G_{RT}$, resulting from the structural arrangements of the longitudinal tracheids and ray cells. The shear values determined are close to the range of those reported for softwoods. Bodig and Jayne [1993] give the ratio of shear modulus in the LR, LT and RT planes as 10:9.4:1, and the E_L to G_{LR} ratio as 14:1. Slightly lower ratios were obtained for Scots pine tested in compression (9.4:8.4:1 at 65% RH). The ratio between E_L and G_{LR} is 14.8 at 65% RH, which is almost identical to the value presented by Bodig and Jayne [1993]. The ratio between E_L and G_{LT} is 16, and the ratio between E_L and G_{RT} determined in the study is 140. Both of these values are also similar to the average for softwoods.

As shown in figure 5, all shear modulus values decrease significantly with increasing MC ($p < 0.05$; $R^2 = 0.79$). With a decrease of 31% over the measured MC range, the decrease is most pronounced for G_{RT}, followed by G_{LR} (29%) and G_{LT} (28%).

The shear modulus of wood has practical importance, because 15% of the deformation occurs due to shear in bending [Divos et al. 1998]. Comparison of the shear properties determined by different test methods is difficult, in view of the accompanying secondary stresses. Investigations have shown different shear modulus values from different test methods as a result of the stress distributions inherent to the test setups [Harrison 2006]. Thus, it is difficult to make direct comparisons between the results of individual research efforts. In general, the ratio between E_L and G_{LR} is 16. This value is commonly accepted for structural applications, but investigations have shown that it may vary between 8 and 65 [Divos et al. 1998; Harrison 2006].

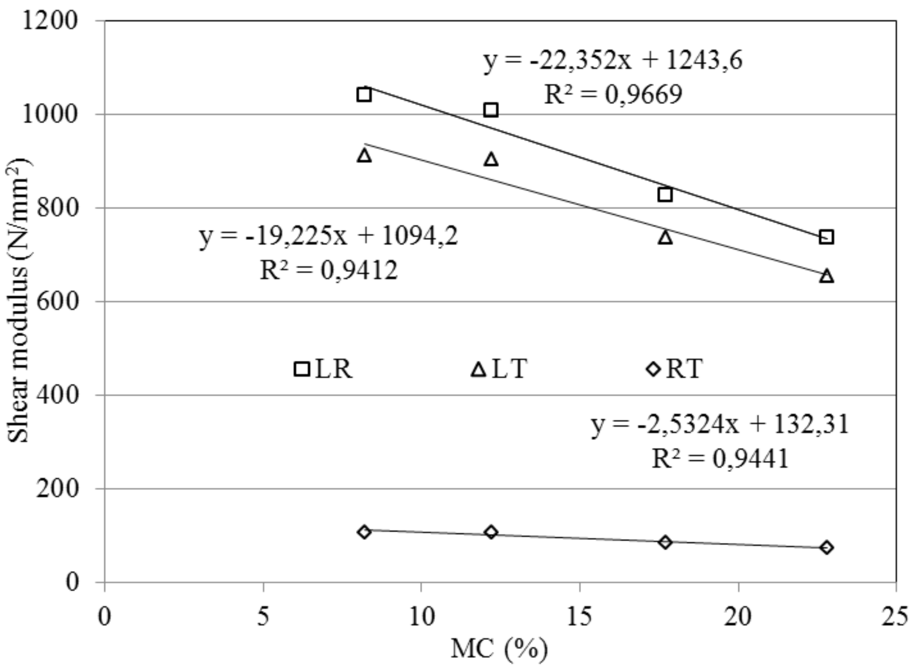

Fig 5. Comparison of shear values as functions of MC

Compared with available Poisson's ratios for softwood species reported by Ross [2010], some of the calculated Poisson's ratios for Scots pine wood are somewhat higher. There is no reasonable explanation for the high Poisson's ratios. However, it should be noted that the perfect elastic orthotropic symmetry assumption for wood may not be fully satisfied.

The coefficient of variation for the Poisson's ratios calculated in the study ranges between 14% and 49%. High coefficients of variation for the Poisson's ratios were also reported by Kretschmann and Green [1996], Jeong et al. [2010], Hering et al. [2012a], Mizutani and Ando [2015] and Ozyhar et al. [2013].

Unlike the Young's modulus and shear modulus, the Poisson's ratios are not affected by MC, and no uniform trend with MC is observed. The Poisson's ratio υ_{TL} calculated from the compression tests increased with increasing MC. The other ratios determined from the compression test appeared to fluctuate with changes in MC.

According to Ross [2010], Poisson's ratios vary within and between species and are influenced by MC and specific gravity. The effect of MC on the Poisson's ratios of wood species as reported in the literature is not consistent. Although no significant effects of MC on the Poisson's ratios were found by Ozyhar et al. [2013]; a slight decrease in the Poisson's ratios with increasing MC was reported by Hering et al. [2012a], and a small increase with increasing MC by Güntekin et al. [2016b]. A significant decrease in the Poisson's ratios in the L direction with increasing MC below fibre saturation point was reported by Kretschmann and Green [1996] and Mizutani and Ando [2015]. The disagreement as to the effect of MC may also be related to the high variation in the Poisson's ratios. Wood is a highly variable material, and for many of its features distinct patterns of variation can be found within a growth ring, outwards from the pith towards the bark, upwards in the tree, and from tree to tree [Dinwoodie 2000]. Figure 6 shows fluctuations in the Poisson's ratios with changing MC. If the values measured at 45% RH are ignored, some of the Poisson's ratios appear to be decreasing.

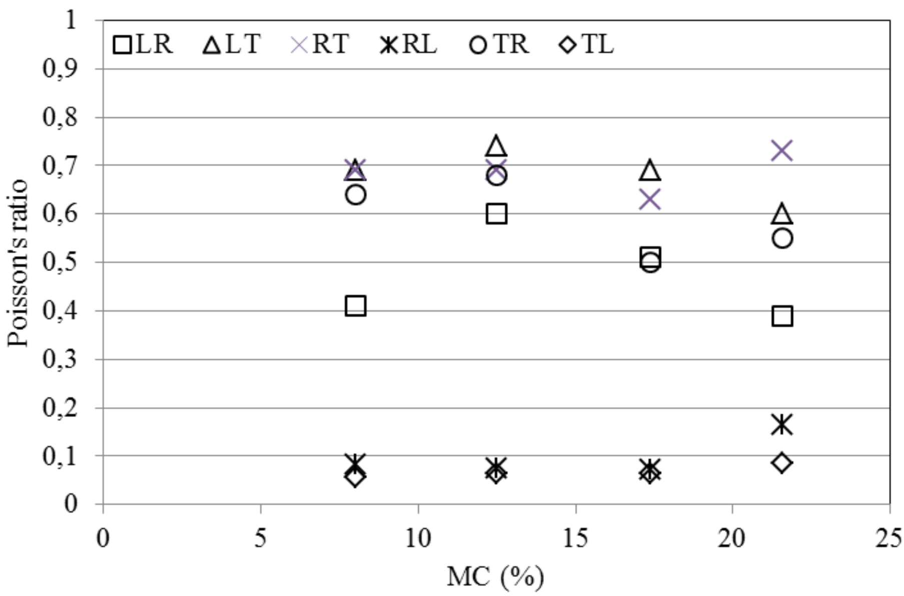

Fig. 6. Effect of MC on Poisson's ratios

The average CS of Scots pine wood tested parallel to the grain is 45.8 N/mm^2 at 12% MC. This value is higher than that reported by Tomczak et al. [2013], but lower than those given by Boonstra et al. [2007], Gurau et al. [2008] and Kamperidou et al. [2014]. It is identical to the value reported by Dinwoodie [2000], Ulker et al. [2012] and Yapıcı et al. [2015].

Test results indicate that CS parallel to the grain is much greater than CS perpendicular to the grain, as expected. Arrangements of the wood fibres play an important role in the mechanical behaviour of wood materials. The presence of ray cells may cause a difference in properties between the radial and tangential directions [Holmberg et al. 1999]. Depending on the wood species, the ratio of CS parallel to the grain to CS perpendicular to the grain varies between 4.8 and 12.4 [Aydın et al. 2007]. The Scots pine wood tested in this study yielded an L/T ratio of 7.1 and an L/R ratio of 11.8 at approximately 12% MC. The CS perpendicular to the grain is particularly important for all contact points between wooden structural members. The values of CS perpendicular to the grain determined in this study are identical to those reported by Juodeikienė [2009], but higher than those given by Boonstra et al. [2007].

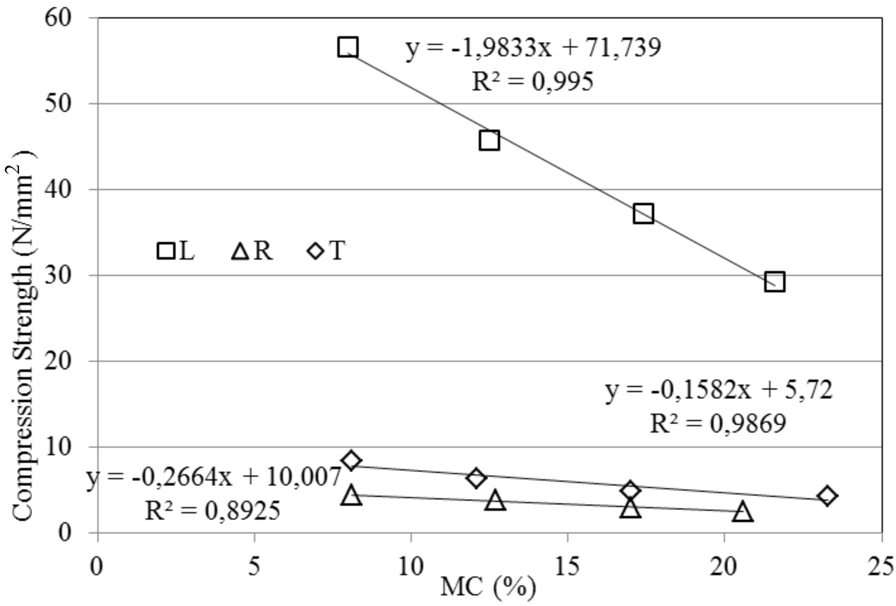

Fig 7. Comparison of CS values as functions of MC

The results indicate that the three CS values are significantly affected by MC ($p < 0.05$; $R^2 = 0.98$). Figure 7 shows that the relationship between CS and MC is almost linear for all directions. The CS values fall by nearly a half within the measured range of increase in MC. Although Dinwoodie [2000] reported a 2% change in the CS of Scots pine timber per 1% change in MC, this study yielded a change of approximately 3.5% in CS per 1% change in MC, which is similar to the result given by Kretschmann and Green [1996]. The percentage decrease is greater for CS parallel to the grain direction.

Conclusions

In this study, Young's modulus, shear modulus, Poisson's ratios and compression strength were measured in three principal directions for Scots pine wood grown in Turkey. The results show that the elastic properties and compression strength values of Scots pine in the three principal directions are significantly different. Decrease is remarkable in elastic modulus and compression strength with increasing MC. The Young's modulus values in the R and T directions are affected by the MC to a significantly greater degree than the value in the L direction. The effect of MC on CS was more significant in the T direction. Unlike the Young's modulus and shear modulus, the Poisson's ratios are not affected by MC and no uniform trend with MC is observed. The results of this study may be utilized in three-dimensional modelling of mechanical behaviour for Scots pine wood.

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