Prediction of Compression Properties in Three Orthotropic Directions for Some Important Turkish Wood Species Using Ultrasound

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Compression properties in three orthotropic directions for some important Turkish wood species, including Calabrian pine (*Pinus brutia* Ten.), Taurus cedar (*Cedrus libani*), Oriental beech (*Fagus orientalis*), and sessile oak (*Quercus petraea*), were studied using non-destructive and destructive techniques. The materials used in the study consisted of 720 small clear specimens of nominal dimensions of 20 x 20 x 60 mm. The influence of equilibrium moisture content (EMC) was studied over four batches of 15 specimens each, conditioned for six to eight weeks before testing at a temperature of 20 ± 2 °C and at four different relative humidity conditions (50%, 65%, 85%, and 95%). Time of flight values were measured with a commercial ultrasonic tester. Using the time results from the ultrasound device, the wave velocities (length/time) and E_{dyn} values were calculated. Samples were also tested in uniaxial compression to determine the Young's modulus and compression strength values in three orthotropic directions. The E_{dyn} correlated well with the Young's modulus and compression strength of the specimens; coefficients of determination ranged between 0.75 and 0.96. Moisture content seems to have more influence than density on sound velocities. Results showed that there is a weak and mostly negative correlation between the density of the specimens and the sound velocity values.

Keywords: Compression; Prediction; Ultrasound

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INTRODUCTION

Compression properties, particularly the Young's modulus, in the three principal directions are important in the design of wood members in structures. Young's modulus, also known as the elastic modulus, is a measure of the stiffness of an elastic material and is a quantity used to characterize materials. In general, there are many physical parameters that may affect the Young's modulus, such as the moisture content (MC), specific gravity, temperature, creep, knots, number of annual growth rings, and grain angle. Investigations regarding the influence of MC on the Young's modulus have shown that if MC increases, the Young' modulus will decrease. While the influence of MC on the mechanical behavior of wood in the longitudinal (*L*) direction is relatively well known (Gerhards 1982a), investigations of the behavior in the perpendicular directions (radial, *R* and tangential, *T*) are limited. Interest in the moisture-dependent orthotropic behavior is not new. So far, only a few studies have investigated the moisture-dependent elastic properties of wood in the *R* and *T* directions (McBurney and Drow 1962; Hering *et al*. 2012a,b; Ozyhar *et al*. 2013a,b). Furthermore, moisture-dependent wood strength in the *R* and *T* directions remains unrevealed for most wood species. The usable data is limited to a few references (Kretschmann and Green 1996; Ozyhar *et al*. 2013a,b), while selected moisture-dependent elastic properties for some wood species have also been reported (Kretschmann and Green 1996; Ross 2010).

The Young's modulus can be determined using both destructive and non-destructive methods. Use of non-destructive testing (NDT) and non-destructive evaluation (NDE) in the field of wood and wood-based materials is advancing every day. There are widespread NDT techniques, equipment, and evaluation procedures available today that resulted from early NDT research (Brashaw *et al*. 2009; Dündar and Divos 2014).

Ultrasonic wave velocity has advantages over other techniques in practical terms (Esteban *et al*. 2009). The ultrasonic technique has been utilized in many applications including tree quality evaluations in forests (Wang *et al*. 2004) and condition assessments of wood structures in service (Ross and Pellerin 1994). Determination of the ultrasonic modulus of elasticity in a solid depends on its elastic properties and its density (Oliveira and Sales 2006). The velocity of sound in wood is influenced by factors such as MC, grain orientation, density, decay, temperature, and geometry (Beall 2002; Oliveira *et al*. 2005).

Information on the Young's modulus of wood in the orthotropic directions is not available for the majority of Turkish species. Most studies deal with bending modulus of elasticity (MOE) and bending, tensile, and compression strength at constant MC. Although data are needed for three-dimensional modeling of mechanical behavior depending on the MC change, no information is available for this purpose. In this study, the Young's modulus in compression for some important Turkish wood species is determined by non-destructive and destructive testing under various moisture conditions.

EXPERIMENTAL

Materials

For this study, two softwood and two hardwood species were chosen. The sample trees of sessile oak (*Quercus petraea*) and Oriental beech (*Fagus orientalis*) were harvested from a beech-oak mixed stand in the Devrek Forest Region of the Western Black Sea region of Turkey. The sample trees of Calabrian pine (*Pinus brutia* Ten.) and Taurus cedar (*Cedrus libani*) were selected from a pine-cedar mixed stand in the Bucak Forest Region of the Southwest region of Turkey. Calabrian pine covers the largest area (3096 064 ha) among conifers grown in Turkey, which corresponds to about 15.3 percent of the total forest area in Turkey. The woods of other selected species are important raw material for various fields of forest industry and have high importance in trade.

The ages of the pine, cedar, beech, and oak trees considered in this work were 60, 80, 140 and 170, respectively. The pine, cedar, beech and oak logs were 37 to 50 cm in diameter at breast height. All the samples came from the sapwood planks cut from the trunk section 1 to 3 meters from the ground level, except for oak, which has very narrow sapwood. 60 samples with nominal dimensions of 20 x 20 x 60 mm for each direction (*L*,*R*,*T*) from radial or tangential planks were prepared.

Prior to testing, specimens were divided into four matched groups conditioned for six to eight weeks at a temperature of 20 ± 2 °C, and at four different relative humidity conditions (50%, 65%, 85%, and 95%). A total of 180 specimens used in testing for each species.

Methods

Apparent densities (ρ) of the samples were calculated according to TS 2472 (2005) using the stereometric method which is based on measurements of the sample volume and mass.

Time of flight values were measured with an ultrasonic commercial device (Steinkamp BP-V, Germany) using conical sensors with a frequency of 22 kHz. Measures were made in end to end directions (*L*, *R*, *T*) on each specimen with a constant sensor coupling pressure, as shown in Fig. 1. According to the time results of the ultrasound devices, the sound velocities (SV, length/time) and E_{dyn} were calculated using the following equation,

$$E_{dyn} = \rho\, V^2\, 10^6 \qquad (1)$$

where E_{dyn} is the dynamic modulus of elasticity, in N/mm^2; ρ is the density, in kg/m^3; and V is the velocity of the ultrasound wave, in m/s.

Fig. 1. Device used to measure time of flight

After completing ultrasonic measurements, uniaxial compression tests were carried out using a Zwick 100 universal testing machine (Germany) at standard climatic conditions (65% RH and 20 °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 approximately 2.0 mm/ minute and defined in such a way that the failure of the specimen should be reached in 90 (± 30) s. The strain was evaluated using the digital image correlation (DIC) technique. A high-contrast random dot texture was sprayed on the surface of the specimen with an air-brush to ensure the contrast needed for the evaluation of the displacements. Images of the cross-sectional surface area of the specimen during testing were acquired with a frequency of 4 Hz (Fig. 2). Using mapping software (VIC 2D, Correlated Solutions, USA), the surface strain was calculated from the displacement that occurred during deformation. A more detailed description of the strain computation by the DIC technique is given in Keunecke *et al.* (2008). The stress-strain curves obtained were used to evaluate the Young's modulus and compression strength of the specimens. The Young's modulus was calculated from the ratio of the stress, σ, to the strain, ε, measured in the linear elastic range:

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

Because the strength behavior of wood in the *R* and *T* directions is obscure, the maximum compression strength was calculated using 0.2% yield values using the following formula,

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

where σ_{UCS} represents the yield strength, $P_{\max}$ is the yield load, and *A* is the cross-sectional area of the specimen.

The analysis of variance (ANOVA) general linear model procedure (SAS Institute Inc., USA) was used to interpret the interrelationships among the properties measured for the clear wood samples.

Fig. 2. Compression test set-up

RESULTS AND DISCUSSION

Average values for density, MC, sound velocity (SV), E_{dyn}, Young's modulus, and compression strength (CS) of the specimens tested are presented in Tables 1 through 4. There was a good match among the density values in the various MC groups. In comparison to available literature references for similar MC, the measured density values were comparable. The relationships between E_{dyn} and Young's modulus and E_{dyn} and CS are presented in Figs. 3 through 6.

The SV values obtained in this study were similar to those reported by Bucur (2006), except for sessile oak, which has much lower SV values than common oak and many hardwood species. Results indicate that there was a weak negative correlation between density and SV for each species tested. There is a contradiction in the literature on whether SV is correlated with wood density or not. Some authors (Oliveira *et al.* 2002; Ilic 2003; Teles *et al.* 2011) determined that there is no relationship between density and velocity, while others (Oliveira and Sales 2006; Baradit and Niemz 2012) reported a positive relationship between density and velocity. Some authors (Ilic 2003; Krauss and Kúdela 2011) claim that velocity is related to the micro-fibrillar angle, while Gerhards (1982b) and Beall (2002) pointed out that grain angle has a major impact on the SV.

Table 1. Sound Velocity, E_{dyn}, Young's Modulus, and CS Values for Calabrian Pine

Relative Humidity (%)	Direction	Density (g/cm^3)	MC (%)	Velocity (m/s) Mean	cov	E_{dyn} (N/mm^2) Mean	cov	Young's Modulus Mean	cov	CS Mean	cov
50	L	0.53	10.5	5302	3.6	14968	10.2	9131	19	38.4	6.6
50	R	0.53	10.7	2304	4.8	2860	12.0	1114	19	8.7	12.2
50	T	0.55	10.8	1680	4,0	1545	7.5	646	11	7.5	5.3
65	L	0.53	13.4	5045	3.2	13240	8.8	8650	14	33.1	5.7
65	R	0.53	12.7	2261	4.3	2713	10.5	917	16	8.2	10.6
65	T	0.54	13.4	1651	2.9	1480	5.5	624	14	6.7	7.2
85	L	0.52	19.8	5016	4.2	13222	9.3	7731	16	24.4	6.7
85	R	0.54	20.0	2120	6.3	2451	14.9	766	9	5.8	9.2
85	T	0.55	20.0	1570	1.8	1354	3.7	431	14	4.6	4.9
95	L	0.56	24.3	4821	3.4	13085	8.1	7380	13	21.1	5.1
95	R	0.57	24.6	2037	4.2	2360	8.0	676	15	5.2	5.4
95	T	0.56	24.3	1504	1.9	1265	3.6	402	23	3.8	8.2

*cov = coefficient of variation (%)

Table 2. Sound Velocity, E_{dyn}, Young's Modulus, and CS Values for Taurus Cedar

Relative Humidity (%)	Direction	Density (g/cm^3)	MC (%)	Velocity (m/s) Mean	cov	E_{dyn} (N/mm^2) Mean	cov	Young's modulus Mean	cov	CS Mean	cov
50	L	0.54	10.7	4458	5.4	10706	12.8	7857	18	45.8	6.4
50	R	0.58	10.8	2243	2.2	2933	7.9	1298	16	9.8	1.5
50	T	0.58	10.5	1902	5.0	2107	8.0	716	14	6.9	19.0
65	L	0.57	12.8	4388	7.5	10929	11.5	7496	11	41.3	5.9
65	R	0.57	12.8	2142	3.2	2605	11.7	974	21	9.2	13.0
65	T	0.53	14.8	1756	2.1	1641	7.9	663	21	6.1	13.8
85	L	0.62	20.5	4229	9.2	11115	13.6	6831	10	35.8	7.1
85	R	0.57	20.2	2039	2.2	2360	9.4	850	11	7.8	11.6
85	T	0.54	20.7	1678	2.7	1532	8.4	490	19	5.2	10.4
95	L	0.59	26.0	4406	6.6	11428	9.0	6683	18	31.0	8.0
95	R	0.59	26.0	2001	2.8	2387	9.3	809	9	7.1	8.6
95	T	0.56	23.5	1612	2.4	1445	8.0	437	23	4.4	12.8

*cov = coefficient of variation (%)

In general, the results indicated clear differences between the SV along the principal directions ($SV_L > SV_R > SV_T$). The ratios found in this study were somewhat smaller than those reported by Bucur (2006), Keunecke *et al.* (2011), and Baradit and Niemz (2012). There was a good negative correlation between MC and SV, and the correlations are higher in the perpendicular directions. According to Gerhards (1982b), the SV decreases by 1% when the MC increases by 1% within the hygroscopic range. The SV in all directions seemed to decrease with increasing MC, except for sessile oak samples tested at 20 °C and 95% RH, which showed an increase in comparison to the other levels of RH.

Table 3. Sound Velocity, E_{dyn}, Young's Modulus, and CS Values for Oriental Beech

Relative Humidity (%)	Direction	Density (g/cm^3)	MC (%)	Velocity (m/s)		E_{dyn} (N/mm^2)		Young's Modulus		CS	
				Mean	cov	Mean	cov	Mean	cov	Mean	cov
50	L	0.68	10.6	5168	4.0	18235	8.4	14092	24	54.1	23.6
50	R	0.66	10.2	2244	1.4	3302	4.1	2137	26	14.0	7.8
50	T	0.64	10.9	1572	1.8	1586	7.0	902	14	8.4	24.1
65	L	0.69	13.4	5100	5.2	17941	8.9	13360	10	49.0	19.1
65	R	0.67	11.8	2200	1.6	3222	3.1	1684	21	12.6	5.9
65	T	0.64	13.6	1560	2.2	1568	9.0	824	8	7.6	21.6
85	L	0.68	16.5	4792	4.7	15732	8.9	11586	18	38.8	15.7
85	R	0.68	16.5	2070	1.5	2926	3.1	1481	8	10.8	10.6
85	T	0.64	16.6	1500	2.0	1442	8.1	706	11	6.5	38.5
95	L	0.67	20.3	4901	2.5	16176	4.8	10135	12	33.9	14.6
95	R	0.68	20.4	2032	1.0	2794	3.1	1214	10	9.2	15.0
95	T	0.65	20.9	1495	2.4	1455	9.8	616	17	5.9	36.6

*cov = coefficient of variation (%)

Table 4. Sound Velocity, E_{dyn}, Young's Modulus, and CS Values for Sessile Oak

Relative Humidity (%)	Direction	Density (g/cm^3)	MC (%)	Velocity (m/s)		E_{dyn} (N/mm^2)		Young's Modulus		CS	
				Mean	cov	Mean	cov	Mean	cov	Mean	cov
50	L	0.65	12.2	4168	4.6	11239	13.0	8305	30	37.5	24.2
50	R	0.72	11.6	2001	2.6	2890	4.4	2001	21	14.3	8.3
50	T	0.67	11.9	1661	1.3	1864	4.8	1249	12	10.2	13.2
65	L	0.66	12.8	4160	4.6	11505	9.1	7691	21	34.8	15.1
65	R	0.73	13.7	1996	2.8	2895	4.2	1883	31	12.7	7.4
65	T	0.67	14.3	1638	1.0	1792	4.1	1033	15	9.0	17.6
85	L	0.68	20.8	4042	5.9	11088	14.0	6583	32	27.2	13.7
85	R	0.72	18.5	1882	2.4	2560	3.8	1312	25	10.2	12.6
85	T	0.68	20.9	1592	0.7	1729	2.5	892	32	7.5	25.9
95	L	0.70	23.3	3912	7.5	10752	16.3	5016	37	25.3	11.5
95	R	0.79	20.6	2615	3.5	2615	3.5	1132	31	9.6	13.6
95	T	0.68	22.1	1589	1.4	1723	4.1	715	18	7.1	28.5

*cov = coefficient of variation (%)

The rate of change with changing humidity (%) ranged from 0.36 for cedar in the *L* direction to 1.38 for cedar in the *T* direction. SV in Calabrian pine showed the closest rate of decrease with increasing MC, confirming the results of Gerhards (1982b). In the *L* and *T* directions, sessile oak wood showed a very low rate of decrease in sound velocity with increasing MC. The effect of MC on velocity has been studied by a number of researchers, who have shown that the velocity of acoustic waves decreases with moisture content up to the fiber saturation point (Booker *et al.* 1996; Bucur 2006; Gao *et al.* 2011).

The wood species tested clearly differed regarding their calculated Young's modulus. Between softwoods, the values of cedar were lower than those of Calabrian pine, although cedar had slightly higher average density (0.56 g/cm^3) than Calabrian pine (0.54 g/cm^3). Between hardwoods, sessile oak wood had higher density (0.69 g/cm^3) than Oriental beech (0.66 g/cm^3), but its average calculated Young's modulus values were lower.

The E_{dyn} calculated from sound propagation was much higher than the static Young's modulus because the measurements were not corrected with the Poisson ratios. According to Bucur (2006), the ultrasonic values of Young's modulus, E_L, are slightly higher than the corresponding static measured modulus under compression. It is known that dynamically determined elastic properties are increased by 10% to 20% (or even more, depending on the frequency of ultrasonic waves) compared with statistically calculated values (Keunecke *et al.* 2011).

In general, Young's modulus in all anatomical directions tended to increase at lower MC, as expected. The three Young's modulus values were affected by moisture, but to a different degree. Young's modulus in the direction perpendicular to the grain changed with MC at higher rates. It seems that anisotropy was higher for Oriental beech and Calabrian pine than sessile oak and cedar. It was reported by Baradit and Niemz (2012) that anisotropy is higher in softwood than hardwoods in Europe, while it is the opposite for some Chilean wood species. Bodig and Jayne (1993) stated that the E_L:E_T ratio is nearly 24:1 in softwoods, while Bucur (2006) reported the largest E_L:E_T ratio is nearly 28:1 for Scots pine.

Similar trends in mechanical properties with MC changes were reported by Gerhards (1982a), Ross (2010), Hering *et al.* (2012a), and Ozyhar *et al.* (2013a). The ratio of Young's modulus in the *L*, *R* and *T* directions was approximately 16:2:1 for Oriental beech, which is identical to European beech (Hering *et al.* 2012a). Sessile oak had the lowest difference between the parallel and perpendicular to the grain values, which is similar to results reported by Bucur (2006) and contrary to those reported by Baradit and Niemz (2012) for Chilean hardwoods. The ratios calculated in this study are clearly less than those published by Bodig and Jayne (1993).

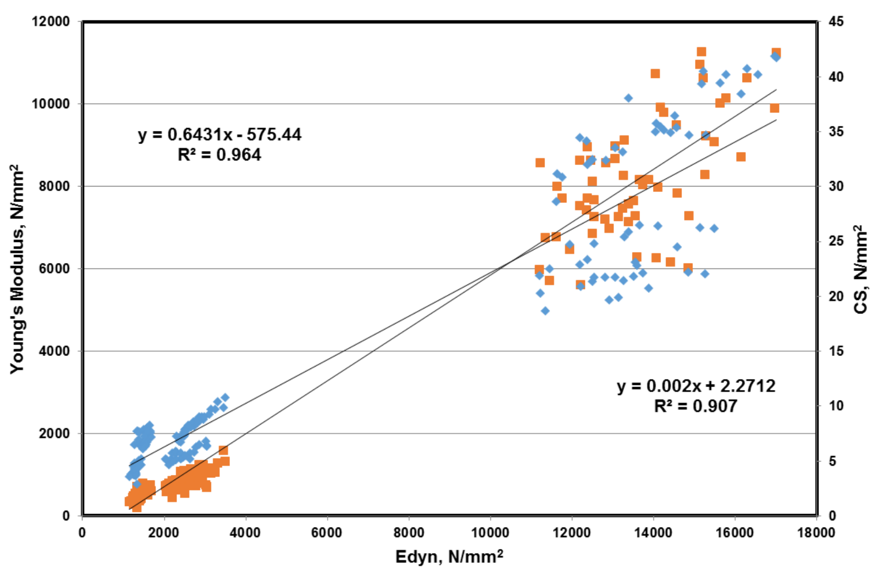

Fig. 3. Estimation of Young's modulus and CS for Calabrian pine

Depending on the type of species, the ratio of CS parallel to the grain to that perpendicular to the grain varied between 3.54 and 6.64, which was lower than those reported for poplar, fir, and pine (Aydın *et al.* 2007) and similar to those stated by Kretschmann and Green (1996). The corresponding values were 6.69 for cedar and 3.54 for sessile oak because of its lower anisotropy. The ratios for the principal direction were almost constant for sessile oak, higher with increasing MC for Calabrian pine, and lower with increasing MC for Oriental beech and cedar. The effect of MC on CS was the highest for Calabrian pine, while it was the lowest for cedar. Figures 3 through 6 show that there was a high correlation between E_{dyn} and compression properties considering all anatomical directions. In non-destructive evaluation of wood, R^2 values are usually dependent on the methods, species used, moisture content, type of samples tested, *etc*. As stated by Ross and Pellerin (1994) that the R^2 values can be as high as 0.98 and 0.88 for clear wood species and dimension lumber, respectively. Divos and Tanaka (2005) reported that R^2 values between static and dynamic MOE values can be between 0.90 and 0.96.

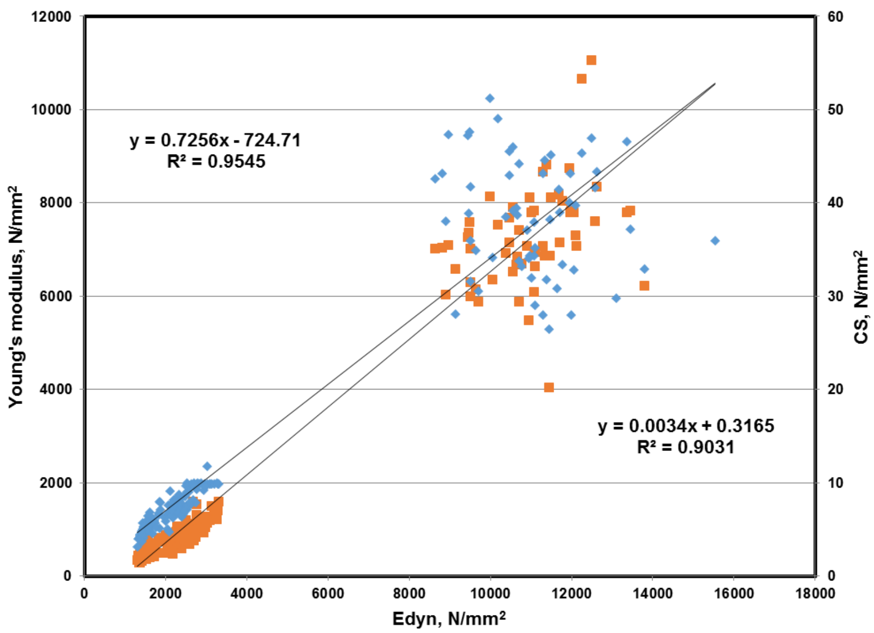

Fig. 4. Estimation of Young's modulus and CS for Taurus cedar

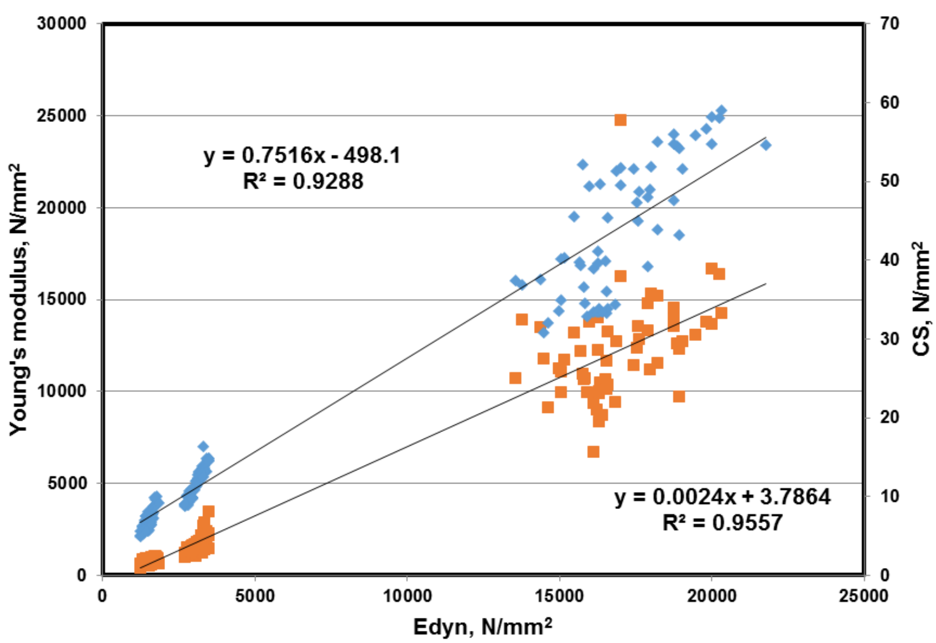

Fig. 5. Estimation of Young's modulus and CS for Oriental beech

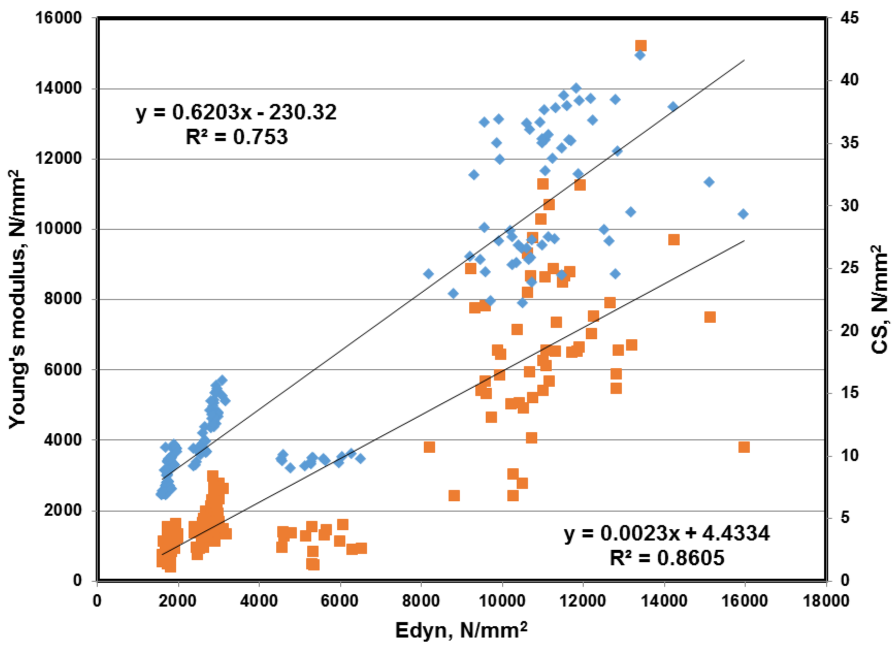

Fig. 6. Estimation of Young's modulus and CS for sessile oak

CONCLUSIONS

1. Compression properties of species tested in all anatomical directions can be predicted using sound velocity. The coefficient of correlations between E_{dyn} and Young's modulus and between E_{dyn} and CS are significantly high.
2. The ratios of E_{dyn}, Young modulus, and CS in principal anatomic directions are similar to those reported in the literature.
3. The effect of MC on SV is more pronounced than is the density of the samples. The differences between the values parallel and perpendicular to the grain for the species tested seem to be influenced by the MC. In general, the ratio between the main directions increases with increasing MC.
4. The Young's modulus in principal directions was significantly different among the species tested. Sessile oak showed the minimum variability, while oriental beech showed the maximum.
5. Compression strength is more sensitive to MC than elasticity for the species tested.

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