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RADIAL VARIATION OF MECHANICAL PROPERTIES OF PINE WOOD (*PINUS SYLVESTRIS* L.) DETERMINED UPON TENSILE STRESS

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ABSTRACT

Specific parameters of strength and modulus of elasticity of pine wood (*Pinus sylvestris* L.), were measured upon tensile stress of microtome samples of early and latewood along the grains as a function of cambial age of annual rings. Measurements were made on samples from two trees occupying a dominant and intermediate positions in the stand. An interesting result is that the density of earlywood shows a clear tendency to decrease with increasing age of the cambial age of annual rings, irrespective of the tree biosocial position. The tensile strength of this wood, although showing fluctuations in particular rings, increases with increasing cambial age of the rings. As to the latewood, its increase in density with increasing cambial age of the rings is limited to juvenile wood zone, up to ring 30th, for further rings the wood density slightly decreases. Although changes in the latewood density as a function of the cambial age of annual rings in the dominant and intermediate trees are insignificant, the analogous changes in the tensile strength are much more pronounced, also in specific tensile strength. The differences in the dynamics of the trees growth in thickness are not reflected in the specific modulus of elasticity.

KEYWORDS: Pine wood, density, MFA, specific strength, specific modulus of elasticity.

INTRODUCTION

Because of its attractive high strength in relation to density, wood is a valuable construction material. The relation between strength and density is referred to as the specific strength, while that between strength and weight density has been defined as the coefficient of strength quality expressed in the units of length. The specific strength or specific modulus of elasticity are very useful when analysing changes in mechanical parameters of wood from the same tree, from different trees of the same or different species as its use permits elimination of the variable wood density. The use of these parameters permit concluding about the influence of factors other then density on the mechanical parameters of wood, in particular on the shape and size of the cells and quality of cell walls. The quality of cell walls is determined by chemical composition and distribution of structural compounds in individual layers. The secondary walls of xylem are usually built of three layers: S1 with transversal arrangement of cellulose microfibers, S2 – a thick layer in which cellulose microfibrils are nearly perpendicular to the longitudinal axes of the cells, S3 with cellulose microfibers in spiral and transversal arrangement (Wardrop and Preston 1947, Preston and Wardrop 1949, Harada et al. 1951, Preston 1952, Meylan and Butterfield 1978, Butterfield and Meylan 1980, Brändström et al. 2003, Brändström 2004a, b, Donaldson and Xu 2005). This structure of the cell wall is optimum from the viewpoint of mechanics of a growing tree (Cave and Walker 1994) as it ensures high stiffness, high strength and high resistance to breaking. The S2 layer makes from 79 to 86 % of the thickness of the cell wall (Fengel and Stoll 1973) so the properties of this layer and cell wall packing determine the properties of solid wood. The cell wall properties are chiefly dependent on the angles made by microfibrils to the longitudinal axes of the cells. The angle of microfibrils from S2 secondary cell wall is not constant. It depends on the tree species and type of cells (e.g. Lichtenegger et al. 1999, Wang et al. 2001), and for trees of the same species and for the same type of anatomical elements the value of this angle depends on the cambial age of the annual rings, position of the cell in the ring and at the height of the tree as well as on the ecological conditions of tree growth (e.g. Cave and Walker 1994, Ying et al. 1994, Sahlberg et al. 1997, Lichtenegger et al. 1999, Anagnost et al. 2002, Lundgren 2004, Jordan et al. 2007, Fabisiak and Moliński 2008, Via et al. 2007, 2009). In general the in the walls of the first cells grown in the beginning of the vegetation period, the angles of microfibrils to the longitudinal cell axes are greater than in the cells grown in the end of the vegetation period (Abe et al. 1992, Anagnost et al. 2002, Fabisiak and Moliński 2007a, b, Fabisiak et al. 2009).

Analysis of the relations between the microfibril angle (MFA) in the walls of tracheids and mechanical parameters of wood stretched along the fibres has shown that the strength of wood and cell walls and the modulus of elasticity are the higher the smaller MFA, but these relations are usually nonlinear (Mark 1967, Mark and Gillis 1973, Cave 1976, Armstrong et al. 1977, Dinwoodie 1981, Cave and Walker 1994, Reiterer et al. 1999, Groom et al. 2002a, b, Moliński and Krauss 2008, Krauss 2010). The character of radial variations in specific tensile strength and specific modulus of elasticity in early and late spruce wood is practically a mirror reflection of the character of changes in MFA in cell walls in these zones (Roszyk et al. 2010).

Because of the MFA variation in cell walls, the mechanical strength of wood of the same density can differ significantly (e.g. Bunn 1981, Bamber and Burley 1983, Zhang 1997) and the same is true for the modulus of elasticity (Cowdrey and Preston 1966 (after Cave and Walker 1994), Cave 1968, Bendtsen and Senft 1986). Recently, Roszyk et al. (2010) have shown that the difference in spruce wood density within the same ring of 2.7 times corresponds to 5 times increase in the modulus of elasticity. Thus, density of wood cannot be treated as the only determinant of its mechanical properties (Walker and Woollons 1998). According to Bendtsen and Senft (1986) as well as Cave and Walker (1994), the main parameter determining the rigidity and strength of wood in longitudinal direction is the microfibril angle in S2 layer of the secondary cell wall. Earlier Cave (1968) has shown that the rigidity of cell wall increases fivefold when the mean MFA decreases from 40 to 10°. Via et al. (2009), have reported fourfold increase in the wood rigidity upon MFA decrease from 40 to 5°. They have studied the effect of lignin and cellulose content, MFA, wood density and position along the radius of the tree in the wood of *Longleaf pine* on the strength and rigidity by near infrared spectroscopy and X-ray diffraction methods.

The aim of the study was to analyse the variation in the specific tensile strength parameters and modulus of elasticity of pine wood (*Pinus sylvestris* L.), measured upon stretching of microtome samples of early and late wood along the fibres in relation to the cambial age of annual rings. It was expected that the analysis of changes in the specific tensile strength and specific modulus of elasticity would show the influence of cell wall quality determined by MFA on the mechanical parameters of wood.

MATERIAL AND METHODS

Radial gradient of mechanical parameters was studied in pine wood (*Pinus sylvestris* L.) from two trees, one from the dominant and one from the intermediate stand, in the age of 62. The trees selected for the study had a cylindrical straight trunk and evenly distributed crowns. The diameter of the tree from the dominant stand at a height of 1.3 m was 32 cm, while that of the tree from the intermediate stand was 23 cm. The tree from the dominant stand was 24.5 m tall, while that from the intermediate stand was 23 m tall. Starting from the breast height of the trees, the bolts were cut out of about 70 cm in length, from which central planks were cut of 60 mm in thickness. Each plank was sawn along the pith. From the north part of each bolt a board of 13 mm in thickness was cut out so that the annual rings ran tangent to the board thickness. Then, the boards were subjected to planting to reduce their thickness in tangent direction to 10 mm. Having determined the zones in which the annual rings were parallel to the pith, smaller sections of 10 cm in length were cut out from these zones. After cutting off a strip of about 1 cm in thickness from the board end, the boards were subjected to plasticisation by heating in distilled water at 100°C for about 35 hours. Then, with the use of slide microtome the samples of about 0.2 mm in thickness were sliced from the earlier marked annual rings. The samples were ordered in the sequence of cutting, placed on a filtration tissue and labelled in the way permitting identification of their position in the annual ring. From each annual ring, from a few to a few tens samples were made, depending on the ring width. A scheme of sample preparation is given in Fig. 1.

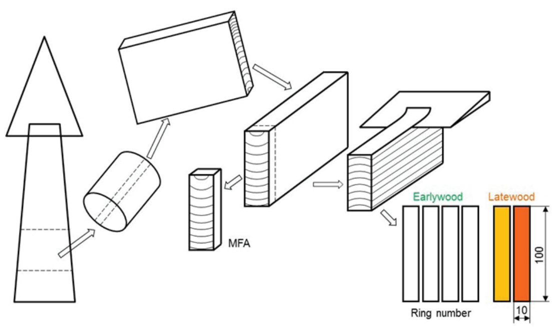

Fig. 1: Schematic presentation of sample preparation

The series of samples prepared in the above way were conditioned in laboratory (T = 21°C, RH = 33-41 %) to reach equilibrium moisture content. When the masses of the samples were stabilised, the widths of the samples were measured by an electronic growth ring measuring device BIOTRONIK, to the accuracy of 0.01 mm, and their thicknesses were measured by a micrometer screw to the accuracy of 0.001 mm at the middle of their length and at about 2 cm from this middle point. The lengths of the samples were measured by a metric rule. Each sample was weighted on a laboratory balance to the accuracy of 0.001 g and density of each sample was calculated. Prior to subjecting the samples to tensile stress, their ends were strengthened by covering with hardboard of 3 mm in thickness and 2 cm in width over the terminal 2 cm long sections. Preliminary tests have shown that such protective covering of the sample successfully protected the samples against damaging in the jaws of the testing machine.

The testing machine was ZWICK ZO50TH with an extensometer of BTC-EXMARCO.001 type. Having introduced to the computer of the testing machine the dimensions of the sample and the extensometer base of 30 mm, the tension stress was applied at the rate of 0.5 mm.min^{-1}. The results were assumed correct when the samples broke up near the middle of their length. A scheme of generation of tensile stress and method of deformation measurements is given in Fig. 2.

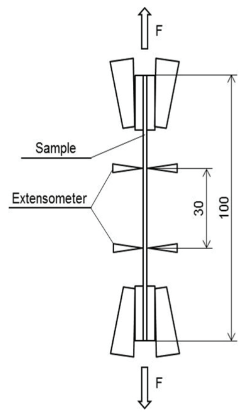

Fig. 2: Scheme of generation of tensile stress and measurement of deformation.

On the stripe cut off each board, at first the width of annual rings and the contribution of latewood in each ring were measured. After these measurements the sample was divided into three parts and each of them was heated in a 20 % solution of $Cu(NO_3)_2$ at 80°C for 24 hours in a water bath. After heating the samples were washed with distilled water at 100°C, for 2 hours. Then tangent microscope preparations of about 0.02 mm in thickness were cut off the same annual rings from which the samples subjected to tensile stress were made. In these microscope preparations the microfibril angle in the tangent walls of tracheids was measured using a computer image analyser. In the same annual ring the preparations were cut off at about every 0.5 mm. After cutting off each preparation, its position in the annual ring was determined with the use of a Brinell gauging magnifier. In each preparation 20 angles were measured. The results were analysed to correlate the specific mechanical parameters of wood with the mean MFA values for particular samples.

RESULTS AND DISCUSSION

Mean densities of wood and mean values of tensile strength and modulus of elasticity were calculated for each sample (for which the results were assumed as correct) of early and latewood from selected annual rings and the values are collected in Tab. 1.

Tab. 1: Mean values of density, tensile strength, modulus of elasticity and microfibril angle in early and latewood of annual rings in the trees studied (A – dominant, B – intermediate).

Biosocial class	Cambial age (years)	Sample size	Density (kg.m^{-3})	Tensile strength (MPa)	Modulus of elasticity (GPa)	MFA (°)
	Earlywood					
A	4	10	314	33.0	4.30	20.9
	12	5	274	23.2	3.73	21.4
	20	5	293	40.2	4.65	21.1
	25	6	250	40.2	4.72	18.4
	30	3	229	34.7	4.75	17.2
	49	4	219	36.0	3.59	19.2
B	3	11	305	28.0	3.70	18.9
	6	5	297	37.1	5.10	13.0
	12	5	257	29.6	3.66	26.0
	20	4	289	45.0	5.40	14.1
	25	2	262	40.9	5.30	16.5
	31	3	213	30.5	4.00	13.2
	49	4	265	48.6	4.60	11.0
	Latewood					
A	4	4	382	36.0	5.70	16.6
	12	3	567	105.3	10.71	18.4
	20	4	709	146.5	15.80	19.5
	25	3	729	168.0	16.19	11.5
	30	1	634	117.7	16.17	10.6
	49	2	688	175.1	21.45	11.3
B	6	2	511	72.0	9.20	9.9
	12	2	611	48.7	14.20	19.2
	20	2	660	84.2	12.00	-
	25	2	681	125.9	21.10	9.8
	31	1	633	121.0	18.90	10.0
	49	3	563	101.3	13.10	12.1

The same table also presents the mean MFA values in tangent walls of tracheids in early and latewood. Analysis of the data from this table shows that the density of earlywood irrespective of the tree, decreases with increasing cambial age of annual rings, while the tensile strength of this wood increases with increasing cambial age, although it fluctuates in particular annual rings (Fig. 3).

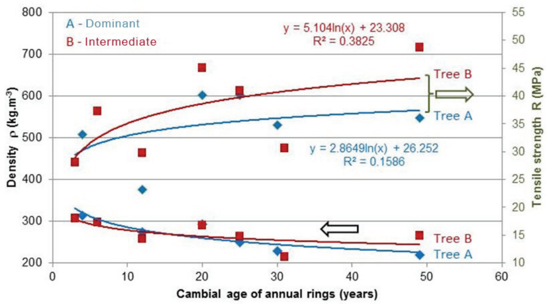

Fig. 3: Radial changes in the mean density and tensile strength of earlywood.

This character of radial variations of these two parameters of earlywood proves that density cannot be treated as the only determinant of wood strength. The density of latewood increases with increasing cambial age of annual tings, although this increase is observed only in juvenile wood (Fig. 4). In the near-pith rings the density changed as follows: The 4th (dominant tree) and 6th (intermediate tree) ring the mean density of latewood was close to 450 kg.m^{-3}, while in the 25th ring it was close to 700 kg.m^{-3}. In further rings the density decreased to about 650 kg.m^{-3}.

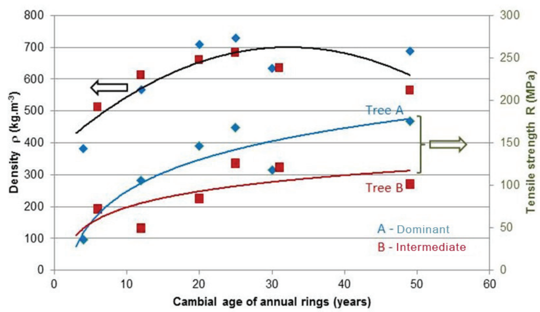

Fig. 4: Radial changes in the mean density and tensile strength of latewood.

The density of latewood undergoes much greater changes as a function of cambial age than that of earlywood. Similar character of radial changes in density of early and latewood has been reported for other coniferous trees loblolly pine (Megraw 1985, Ying et al. 1994), spruce (*Picea abies*) (Roszyk et al. 2010), *Tsuga heterophylla* (Panshin et al. 1964), *Picea mariana* (Zhang 1998), *Larix kaempferi* (Koizumi et al. 2005). Moreover, the character of radial changes in the early and latewood density seems to be independent of the tree position in the stand. The mean values of densities of the early and latewood are similar in the two trees as is the character of the radial density changes. For this reason in Fig. 4 no distinction is made between the parameters of the dominant tree and intermediate tree. Although the differences in the radial changes of latewood density in the two trees differ insignificantly, the differences in the tensile strength are pronounced. The tensile strength of latewood from the dominant tree is much greater than that of the intermediate tree. The changes in tensile strength of latewood as a function of cambial age of annual ring are the opposite to those of earlywood in both trees, see Fig. 3 and 4. The tensile strength of earlywood from the intermediate tree (except for rings 12 and 31) was greater than that of earlywood of the dominant tree (Fig. 3), while the tensile strength of latewood was greater for the dominant tree (Fig. 4). The above character of the changes is also manifested in the radial changes in the specific tensile strength of early and latewood in the two trees (Fig. 5).

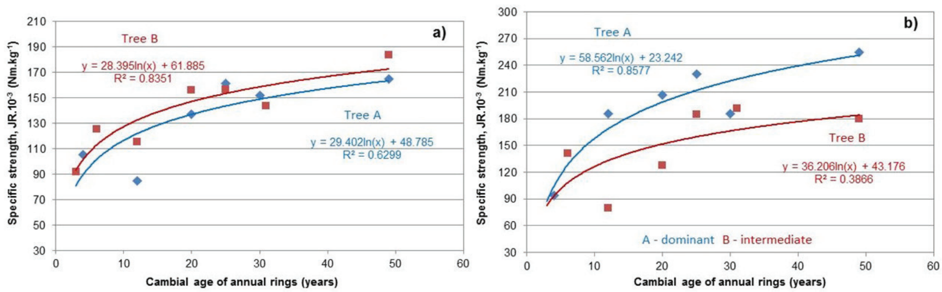

Fig. 5: Specific strength of earlywood a) and latewood b) as a function of the cambial age of annual rings in trees of different biosocial position in the stand.

The specific strength was calculated as the ratio of actual tensile strength of individual samples and their density, according to the formula:

$$JR = \frac{R}{\rho} x\ 10^6$$

where: JR – specific tensile strength ($N.m.kg^{-1}$),
R – tensile strength (MPa),
ρ – density ($kg.m^{-3}$).

The character of radial changes in tensile strength of early and latewood, especially in mature wood, indicates that the dynamics of the tree width growth affects to some degree the technical quality of cell walls. The wood from the tree of slower width growth shows smaller cyclic inhomogeneity in tensile strength (smaller differences within individual annual rings). Analysis of radial variations of the specific tensile strength suggests that this is determined by the properties of latewood, as the differences in tensile strength are the greatest in latewood.

Differences in the dynamics of the tree width growth are not manifested in the modulus of elasticity (Fig. 6) as the characters of radial variation of this parameter for early and latewood are similar for both trees.

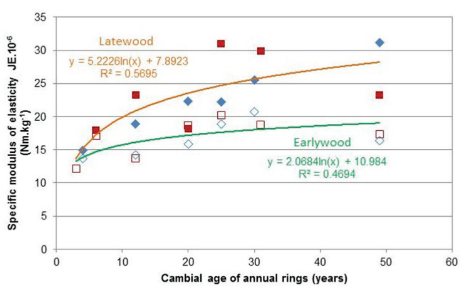

Fig. 6: Radial variation in the specific modulus of elasticity (mean values for two trees) for earlywood and latewood.

For this reason, Fig. 6 presents the radial variation in the modulus of elasticity separately for earlywood and latewood, disregarding the biosocial stand of the trees. No clearly marked influence of the biosocial position of a tree in a stand on the radial changes in the modulus of elasticity in early and latewood proves that the modulus of elasticity is less sensitive to the dynamics of changes in mean MFA in cell walls in both zones of the trees than tensile strength (Tab. 1). Changes in specific tensile strength and modulus of elasticity as functions of cambial age of annual rings evidence variations in the technical quality of wood, determined mainly by MFA (Bendtsen and Senft 1986, Cave and Walker 1994, Reiterer et al. 1999, Groom et al. 2002a, b, Moliński and Krauss 2008). The influence of MFA on specific tensile strength and modulus of elasticity is illustrated in Figs. 7 and 8.

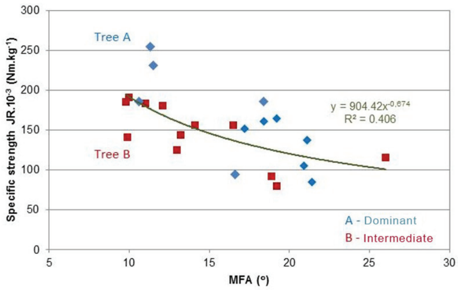

Fig. 7: Specific tensile strength versus the microfibril angle

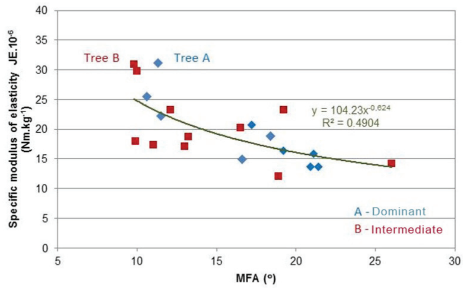

Fig. 8: Specific modulus of elasticity versus the microfibril angle.

Significant influence of MFA is also indicated by the fact that the specific tensile strength and modulus of elasticity measured for early and latewood were similar when the corresponding mean MFA values were similar. The relatively low determination coefficient of the approximation of these variations with a power function follows from the fact that for a mean MFA value for each sample was analysed, while it is known that MFA values can differ significantly even in neighbouring tracheids, generated in the same vegetation period (Anagnost et al. 2002, Fabisiak and Moliński 2008, 2009). Differences in MFA in cell walls is reflected in the inhomogeneous distribution of stress (Reiterer et al. 1999) in the samples so in their different response to loading. The greatest stress is in the walls of the smallest MFA and these walls determine the rigidity of wood tissue. Local stress exceeding the elasticity range, induces changes of the regions responding to the loading and the process of damage of such regions can be abrupt or plastic, depending on the site of initiation and size of defects produced. Thus, a great scatter of values of the specific modulus of elasticity and specific tensile strength at similar mean MFA seems obvious. However, assuming that the plots presented in Figs. 7 and 8 well reproduce the experimental data, it can be read off that when the MFA changes from 10 to 25°, the specific tensile strength decreases on average twice from 0.2 to 0.1 $Nm.kg^{-1}$, while the specific modulus of elasticity decreases 1.8 times, from $25 \cdot 10^{-6}$ to $14 \cdot 10^{-6}$ $Nm.kg^{-1}$. The relation between the specific tensile strength and modulus of elasticity is practically linear (Fig. 9).

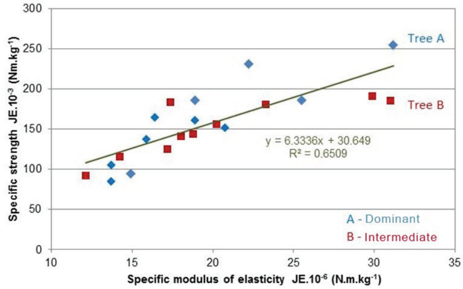

Fig. 9: Specific tensile strength versus specific modulus of elasticity measured upon tensile stress application to microtome wood samples.

As follows from the tensile strength and modulus of elasticity dependence on the density of wood samples studied, shown in Fig. 10, the increase in density from 250 kg.m^{-3} (earlywood) to about 700 kg.m^{-3} (latewood) corresponds to almost fourfold increase in tensile strength, from ~36 to 141 MPa and 4.5-fold increase in the modulus of elasticity, from 4 to 18 GPa.

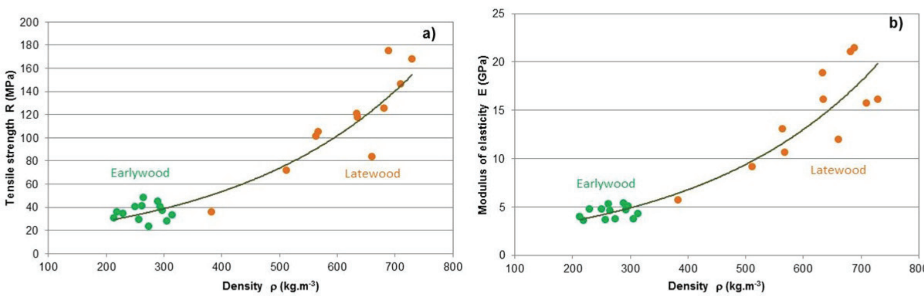

Fig. 10: Tensile strength a) and modulus of elasticity b) versus wood density.

These changes can be related to those in MFA as the latewood samples show the smallest while the earlywood samples the highest mean MFA values. On the basis of the radial changes in the specific tensile strength and modulus of elasticity as well as in their absolute values, it is possible to estimate to which degree the wood density and MFA were responsible for changes in the mechanical parameters of wood. The estimated contribution of MFA to changes in the modulus of elasticity is 40 % (1.8/4.5), while the contribution of density is 60 %; the analogous contributions to the wood density changes are similar (2/4). A smaller influence of MFA on the modulus of elasticity than on the tensile strength can explain the difference in the radial changes in the modulus of elasticity determined by the biosocial position of tree in the stand. It should be mentioned that the mechanical parameters of wood can be affected by other factors such as the size of cells, chemical composition (contribution of structural compounds), degree of polymerisation and crystallisation of cellulose. According to Cramer et al. (2005) variation in the modulus of elasticity of latewood in pine tree (loblolly pine) can be in 75 % explained by changes in density and MFA, but for earlywood the influence of these factors is smaller. However, Megraw (1985) and Ying et al. (1994) claim that these two factors determine the modulus of elasticity changes in the same type of wood in as much as 93 %. A strong correlation between the modulus of elasticity and the two factors: density and MFA, has been also reported for *Pinus* *radiata* by Booker et al. (1997). According to all the authors mentioned above, the wood density and MFA are the main determinants of the rigidity of wood tissue.

CONCLUSIONS

The above presented and discussed results permit drawing the following conclusions:

1. Density of earlywood is practically independent of the biosocial position of a tree in a stand (dominant and intermediate tree) and decreases with increasing cambial age of annual rings. Tensile strength of earlywood generally increases with increasing cambial age of annual rings, although it undergoes some fluctuations within individual rings.
2. Radial variation in the mean density of latewood increases with increasing cambial age of annual rings. The increase in latewood density with increasing cambial age of annual rings is limited to juvenile wood (up to about 30^{th} annual ring); beyond this zone the latewood density slightly decreases. Although changes in the latewood density as a function of the cambial age of annual rings in the dominant and intermediate trees are insignificant, the analogous changes in the tensile strength are much more pronounced, also in specific tensile strength. The tensile strength of latewood in the dominant tree has been proved to be significantly greater than that of latewood in the intermediate tree.
3. Different dynamics of tree width growth is not manifested in changes in the specific modulus of elasticity.
4. The influence of MFA on the modulus of elasticity is smaller than that of wood density.
5. The influence of MFA on the tensile strength is comparable with that of wood density.

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