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MECHANICAL PARAMETERS OF PINE WOOD IN INDIVIDUAL ANNUAL RINGS UNDER TENSILE STRESS ALONG THE GRAINS IN DRY AND WET STATE

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ABSTRACT

The paper presents results of determinations of mechanical parameters of earlywood and latewood of pine (*Pinus sylvestris* L.) subjected to tensile stress along the grains in the wet and air-dry state. Measurements were made on microtome samples obtained from selected annual rings. The immediate mechanical strength, modulus of elasticity and stress at the limit of proportionality were found practically independent of the moisture content, however, the tensile strain at break was much higher in wet state than in air-dry state. For latewood the basic mechanical parameters in the air-dry state were much higher than in the wet state, however the values of tensile strain at break were similar. Moreover, within individual annual rings, the contribution of elastic strain in the tensile strain at break, recorded on application of tensile stress to microtome wet samples of wood along the grains increases with increasing distance from the border of the preceding ring, while for the air-dry samples this contribution decreases.

KEYWORDS: Pine wood, earlywood, latewood, tensile stress, moisture content.

INTRODUCTION

Recently much attention has been paid to the search for relations between wood ultrastructure and its mechanical parameters as it has been established that many of them are determined to a significant degree by the arrangement of microfibrils in S_2 layer of the secondary cell wall with respect to the longitudinal cell axis, expressed by the microfibril angle (MFA). Consequently, the wood density, usually assumed as the main determinant of its mechanical resistance, not necessarily plays this role. Because of MFA variation in cell walls, the mechanical resistance and modulus of elasticity of wood at the same wood density can be much different (Cave 1968, Bunn 1981, Bamber and Burley 1983, Bendtsen and Senft 1986, Cave and Walker 1994, Zhang 1997).

Interestingly, upon tensile stress applied to early pine wood (*Pinus sylvestris* L.) it has been found that despite decreasing density in subsequent annual rings along the radius its mechanical strength can increase (Moliński et al. 2008, Krauss 2010). This observation is related to a decrease in the mean MFA values in the tangent walls of tracheids with increasing maturity of the wood tissue. In other words, with increasing wood tissue maturity the microfibrils of cellulose approach the direction parallel to the longitudinal axes of cells and it is known that the crystalline regions of microfibrils are characterised by high stiffness in this direction. With increasing microfibril angle (MFA), the mechanical properties of cell walls become more dependent on the matrix incrusting the cellulose skeleton, i.e. on hemicelluloses and lignin (Bergander and Salmén 2002, Barnett and Bonham 2004, Gindl and Schöberl 2004, Salmén 2004).

According to Japanese authors (Kojima and Yamamoto 2004a, 2005, Nakai et al. 2006) the arrangement of microfibrils in the thickest layer of the cell wall determines the effect of moisture content on the wood on its modulus of elasticity. For low MFA, a reduction in the modulus of elasticity with increasing moisture content is much greater than for wood with high MFA values. According to these results, the dependence of the mechanical resistance of wood on its moisture content must be related to ultrastructural changes within individual annual rings. In cell walls produced in the beginning of the vegetation period the values of MFA are higher than in the cell walls developing in the end of the vegetation period (Preston 1934, Abe et al. 1992, Saren et al. 2001, 2004, Anagnost et al. 2002, Fabisiak et al. 2006, Fabisiak and Moliński 2007a, Krauss 2007, 2010). Therefore, the tensile strength and elasticity constants of latewood are usually higher than those of earlywood (Wimmer et al. 1997, Moliński and Krauss 2008, Krauss 2010). Not much has been known so far on the mechanical strength of cell walls in latewood and earlywood of different moisture contents.

Preliminary studies performed in the end of 1970s for Douglas fir *(Pseudotsuga menziesii* Franco) have shown that the tensile strength of earlywood along the grains is practically the same in air-dry and wet state, while the tensile strength of latewood in wet state can be even by 50 % lower than that in the air-dry state (Helińska-Raczkowska and Raczkowski 1979).

In view of the above, this study was undertaken to determine the main mechanical parameters of pine earlywood and latewood (*Pinus sylvestris* L.), subjected to tensile stress along the grains in the air-dry and wet (above the fibre saturation point FSP) states. The study was supposed to bring information important from the cognitive and practical viewpoints. The cognitive aspect would be to shed more light on the adsorption enhancement effect, while the practical aspect would be to objectify the interpretation of hygro-mechanical creep of wood (Kojima and Yamamoto 2004b, 2005, Roszyk et al. 2010b and 2012).

MATERIAL AND METHODS

Knowing that the mean MFA in cell walls decreases practically linearly with increasing width of the annual ring (Anagnost et al. 2002), the study of mechanical parameters of wood subjected to tensile stress along the grains versus the wood moisture content was performed on microtome samples of the smallest possible dimension in the radial direction. From a fresh heart plank of 60 mm in thickness a section of 70 cm in length was cut out from the breast height upwards. The section was sawn along the pith and from the north part a board was cut out of 10 mm in thickness measured in tangent direction. From the forehead of the board a strip of wood of 10 mm in length was cut off for measurements of parameters of the annual rings from which samples for the study were to be cut out (width along the radius and contributions of latewood).

The remaining part of the board, after analysis of the run of annual rings in the radial plane, was divided into smaller slats of 90 mm in length and about 45 mm in width. The slats were labelled to identify their position. After plasticization of the wood by boiling in distilled water for 30 hours, the samples of the thickness in the radial direction of about 250 μm were sliced off from the selected annual rings by a sledge microtome. A scheme illustrating the way of sample preparation is given in Fig. 1.

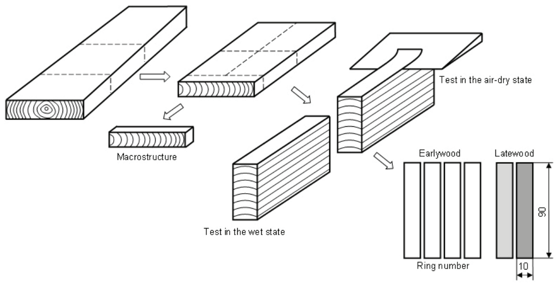

Fig. 1: Scheme illustrating sample preparation.

The choice of annual rings from which the samples were cut out for the study followed from the necessity of making measurements for at least a few samples from earlywood and latewood in the same annual ring. An additional condition was to study the samples representing the possibly widest range of cambial age. Moreover, care was taken to cut out twin samples neighbouring along the tree height in the same annual ring and at the same distance from the ring border. One of the twin samples was used for measurements in air-dry state, while the other in wet state.

After slicing, each sample was labelled and arranged in the sequence of cutting either on a filtration tissue – the samples to be studied in air-dry state or on a Petri dish with distilled water – the samples to be studied in wet state. When the samples to be studied in the air-dry state have reached the state of hygroscopic equilibrium in the laboratory (T = 21 ±1°C, φ = 43 ±2 %), their density was measured by the stereometric method. The mass of each sample was measured in an analytical balance to the accuracy of 0.0001 g, their lengths were measured by a rule to the accuracy of 1 mm, their widths were measured by a Brinell magnifier to the accuracy of 0.1 mm, while their thicknesses were measured by a micrometer to the accuracy of 0.001 mm. The width and thickness of each sample were measured in the middle of its length and at distances of 3 cm from the heads.

Prior to tensile stress application each sample had its ends glued to hardboard pieces of 3 mm in thickness and 2 cm in width, over a length of 2 cm. The hardboard pieces effectively protect the microtome samples against crushing in the holders upon tensile stress application (Moliński et al. 2008, Krauss 2010, Roszyk et al. 2010a, b). To prevent against drying of the samples to be studied in the wet state, they were placed inside special foil envelopes. Having inserted a sample inside the envelope, the excess of air was sucked out from the envelope and it was sealed by thermal compression. The size of the envelopes was a bit greater than that of the samples so that their presence had no effect on the stress and deformation measured.

The tensile stress was applied at the test machine ZWICK ZO50TH equipped with an extensometer of BTC-EXMARCO.001 type. Prior to the test the sample width and thickness were introduced into the test machine computer together with the base of the extensometer of 25 mm, and then tensile stress was applied at the rate of 0.5 mm.min^{-1}. The results were assumed correct for the samples that were broken near the middle of their lengths. Directly after breaking, the moisture content of each sample was determined by the gravimetric method with the use of balance dishes.

RESULTS AND DISCUSSION

Structural parameters (width and percentage of latewood) of the annual rings from which samples to be studied were cut out are given in Tab. 1. The same table also includes the densities of earlywood and latewood in these annual rings, calculated as mean values measured for the respective samples. The data in this table refer to the air-dry wood, of mean moisture content of about 8 %. As follows from these data the mean densities of earlywood in selected annual rings were similar, while the mean densities of latewood decreased with increasing wood maturity. Therefore, it can be concluded that the samples were cut out of the mature tissue as in the zone of juvenile wood density changes are much pronounced (Bendtsen 1978, Helińska-Raczkowska and Fabisiak 1999), while in juvenile zone the latewood density increases in subsequent annual rings counted from the pith (Moliński et al. 2008).

Tab. 1: Parameters of the annual rings from which samples were taken for the study, determined in the air-dry state (MC = 8 %).

Cambial age of annual rings (years)	Annual ring width s (mm)	Percentage of latewood lw (%)	Mean density ρ ($kg.m^{-3}$)	
			earlywood	latewood
21	3.0	33.3	243	749
38	4.0	37.5	232	719
40	3.5	28.6	226	672
62	2.0	25.0	252	657

Changes in the density of wood in air-dry state (MC ~ 8 %) as a function of the width of annual rings are illustrated in Fig. 2. The same figure shows also the results of tensile strength measured for air-dry and wet samples. As follows from these data, the tensile strength of wood increases from the beginning of the annual ring to its end (in radial direction), irrespective of wood moisture content. To improve the clarity of Fig. 2, the results for earlywood, latewood and for the samples classified as transitional are marked by different symbols. Worth noting is the fact that the tensile strength of earlywood in air-dry state does not differ much from that determined for the wood in wet state. The mean values of tensile strength (Tab. 2) of earlywood in air-dry state are comparable to the values obtained for earlywood in the wet state (ring 62) or up to 1.6 times greater (ring 21). In general, for earlywood the mean tensile strength value for all annual rings is by about 20 % higher in air-dry state than the mean value for wet samples. Moreover, the tensile strength of wet latewood is not much different than that of wet earlywood. The tensile strength of latewood in air-dry state is higher. The difference between the tensile strength of air-dry and wet latewood markedly increases with the vegetation season. The mean tensile strength of latewood (Tab. 3) in the air-dry state is from 1.9 (ring 38) to 3.1 (ring 62) higher than in wet state, on average it is by 2.7 times higher. It should be noted that the data from Tabs. 1-3 do not refer to the samples from the transition zone between the early- and latewood.

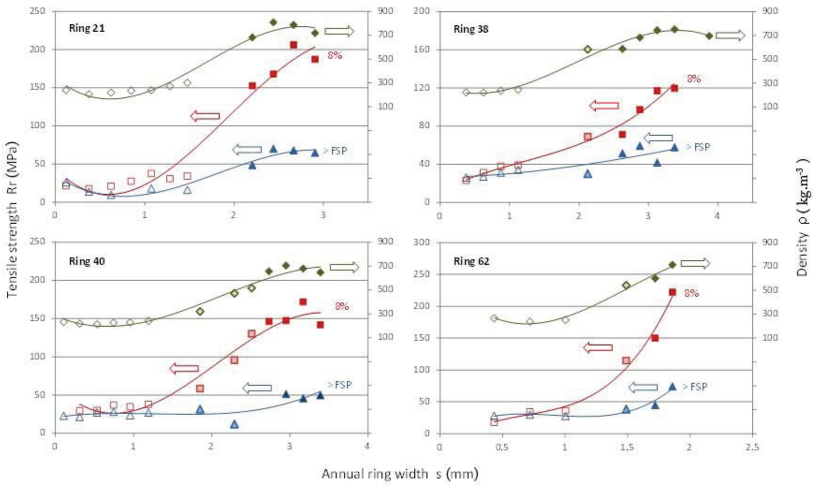

Fig. 2: Variation in the density and tensile strength of pine wood in the air-dry state (MC = 8 %) and the wet state (MC > FSP) in particular annual rings.

Tab. 2: Mean mechanical parameters of earlywood subjected to tensile stress along the grains for different moisture contents.

Cambial age of annual rings (years)	Tensile strength, R_T (MPa)		Modulus of elasticity, E (GPa)		Stress at proportional limit, σ_{pl} (MPa)		Strain at break, ε (%)	
	MC 8 %	MC > FSP	MC 8 %	MC > FSP	MC 8 %	MC > FSP	MC 8 %	MC > FSP
21	27.1	16.5	4.63	2.57	17.2	10.7	0.67	1.12
38	32.8	29.7	3.58	1.81	16.7	13.6	0.95	3.04
40	33.7	25.0	3.45	1.53	13.8	11.7	1.14	2.91
62	29.3	28.4	3.58	2.08	13.0	13.2	1.02	1.85

Tab. 3: Mean mechanical parameters of latewood subjected to tensile stress along the grains for different moisture contents.

Cambial age of annual rings (years)	Tensile strength, R_T (MPa)		Modulus of elasticity, E (GPa)		Stress at proportional limit, σ_{Xpl} (MPa)		Strain at break, ε_X (%)	
	MC 8 %	MC > FSP	MC 8 %	MC > FSP	MC 8 %	MC > FSP	MC 8 %	MC > FSP
21	178.5	63.0	21.00	5.30	66.9	11.5	0.83	0.68
38	101.3	52.7	14.86	5.71	45.7	19.6	0.85	1.25
40	151.9	49.1	15.35	1.90	43.8	19.5	1.21	0.70
62	186.1	59.6	25.01	9.00	151.6	17.7	0.90	1.00

Analysis of the mean values of tensile strength of earlywood (Tab. 2) and latewood (Tab. 3) shows that there is no clear correlation between this mechanical parameter and the mean density of wood (Tab. 1). The mean tensile strength of air-dry earlywood from subsequent rings from ring 21 to 40 increases (from 27 to 34 MPa), while the mean densities of wood in the same annual rings decrease (from 243 to 226 $kg.m^{-3}$). These results provide another evidence showing that wood density is not a reliable parameter determining the tensile strength. The same can be concluded about the other mechanical parameters whose values are presented in Tabs. 2-3: modulus of elasticity, tensile stress at the limit of proportionality and relative tensile strain at break.

The mean values of modulus of elasticity of earlywood from all annual rings considered in Tabs. 2-3, are on average 1.9 times higher in the air-dry than in the wet state. However, the mean modulus of elasticity of latewood in air dry state is as much as 3.5 times higher than in the wet state. Similar relations were observed for the mean tensile stress at the proportionality limit; mean values of this parameter for earlywood are on average only 1.2 times higher in the air-dry state than in the wet state, while for latewood the analogous values in the dry state are 4.5 times greater than in the wet state.

The reverse relation was observed when analysing the relative tensile strain at break, Fig. 3. According to Tab. 2, this parameter for wet earlywood was from 1.6 (ring 21) to 3.2 (ring 38) times higher than for air-dry earlywood, the mean difference for all annual rings considered was 2.4 times. The latewood was broken at similar values of tensile strain irrespectively of the moisture content, see Tab. 3. The ratio of mean tensile strain at break for latewood in the wet state to that in the dry state was close to unity (0.96). In view of the fact that the values of modulus of elasticity and stress at the limit of proportionality for earlywood were practically independent of its moisture content, while for latewood the influence of moisture content on these parameters was significant, the above result seems surprising. Trying to explain these results, for individual samples the contributions of their relative strain at the limit of proportionality to the tensile strain at break (damaging strain) were determined for individual samples. The values of so determined coefficient versus the width of annual rings studied, for the wood of different moisture contents, are presented in Fig. 4. Analysis of these data shows that for the wet earlywood the strain at the limit of proportionality brings a smaller contribution in the strain at break in comparison with that for earlywood in air-dry state. For latewood the relation is the opposite. These results seem to confirm the earlier observations by other authors. According to Burgert (2006), who studied the variation in MFA upon immediate tensile stress applied to a reaction wood of spruce (*Picea abies*), above the strain at the limit of proportionality the values of MFA considerably decrease. Moreover, in the test when tensile stress was applied to individual tracheids, the stiffness of cell walls increased above certain value of tensile strain, especially in the cells with relatively high MFA values (Sedighi-Gilani and Navi 2007). Therefore, in the earlywood in which MFA values are higher than in latewood (Moliński and Krauss 2008, Moliński et al. 2008) the microfibrils could have undergone reorientation responsible for increased strain above the limit of proportionality.

The differences in wood performance depending on the MFA value has also been observed upon wood creep (Kojima and Yamamoto 2004b, 2005, Roszyk et al. 2010b, 2012). It is supposed that with increasing MFA, the deformation caused by the creep is to an increasing degree determined by the viscous behaviour of the matrix incrusting the cellulose skeleton. For small MFA the process of wood creep is mainly determined by the local (in the amorphous regions) viscoelastic behaviour of the cellulose skeleton (Kojima and Yamamoto 2004b, 2005).

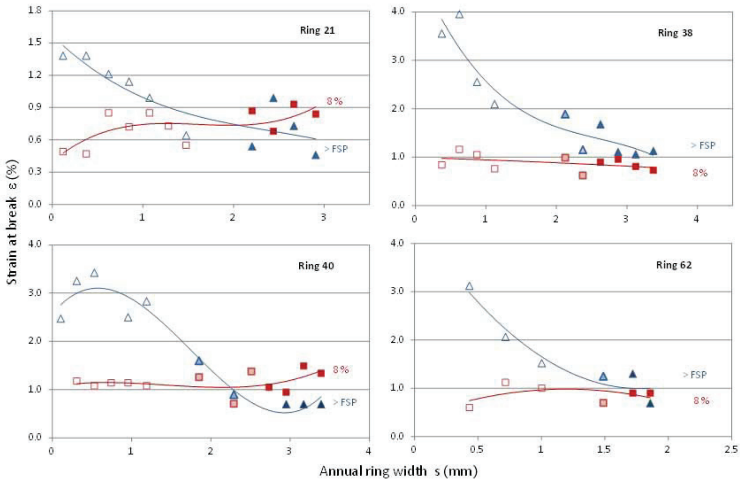

Fig. 3: Tensile strain at break in pine wood subjected to tensile stress along the grains in the air-dry state (MC = 8 %) and the wet state (MC > FSP) in particular annual rings.

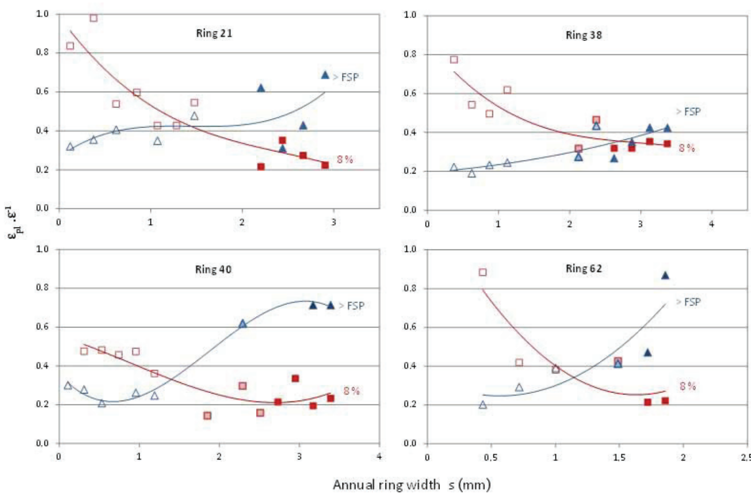

Fig. 4: Variation in the contribution of tensile strain at the proportionality limit to the tensile strain at break for pine wood subjected to tensile stress in the air-dry state (MC = 8 %) and the wet state (MC > FSP) in particular annual rings.

The results presented in this work surely need a deeper analysis made taking into regard the MFA measurements, which has been already undertaken and will be a subject of a separate paper.

CONCLUSIONS

Analysis of the above presented and discussed results permits drawing the following conclusions:

1. Fundamental mechanical parameters of earlywood under tensile stress applied along the grains, such as immediate strength, modulus of elasticity, stress at the proportionality limit are practically independent of its moisture content. However, earlywood in the wet state breaks at higher tensile strain than in the air-dry state.
2. Although the fundamental mechanical parameters of latewood under tensile stress in the air-dry state re much higher than in the wet state, latewood in both states of moisture content breaks at comparable values of tensile strain.
3. Within individual annual rings, the contribution of elastic strain in the tensile strain at break, recorded on application of tensile stress to microtome wet samples of wood along the grains increases with increasing distance from the border of the preceding ring, while for the air-dry samples this contribution decreases.

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