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DIFFERENCES IN THE MECHANICAL PROPERTIES OF EARLY AND LATEWOOD WITHIN INDIVIDUAL ANNUAL RINGS IN DOMINANT PINE TREE (*PINUS SYLVESTRIS* L.)

Andrzej Krauss, Waldemar Moliński
Poznań University of Life Sciences, Faculty of Wood Technology
Poznań, Poland

Jozef Kúdela, Igor Čunderlík
Technical University in Zvolen, Faculty of Wood Science
Zvolen, Slovak Republic

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ABSTRACT

We investigated the reasons for the differences in the tensile strength and elasticity modulus of wood and cell walls between earlywood and latewood tracheids of pine (*Pinus sylvestris* L.). These two stress characteristics were determined by tensile strength tests along the grain as functions of the cambial age of the annual rings. The results showed that the tensile strength and elasticity modulus of earlywood were practically independent of the cambial age of the annual rings, while those of latewood increased with the increasing cambial age. The elasticity modulus of the cell walls of early tracheids varied from 21 GPa to 31 GPa, while in the cell walls of late tracheids it increased with the increasing cambial age of annual rings from 23 GPa to 47 GPa, on average. The fundamental reason for changes in the elasticity modulus of cell walls of early and latewood tracheids was the change in the microfibril angle. The tensile strength of earlywood was fully determined by the strength of the cell walls, while the tensile strength of latewood was determined in 60 % by the strength of the cell walls and in 40 % by the wood density.

KEYWORDS: Wood density, tensile strength, modulus of elasticity, cell wall, microfibril angle.

INTRODUCTION

Given the current state of knowledge it is a truism to claim that the mechanical strength of a material depends on its structure or strictly speaking on the energy of bonds between the molecules which this material is made of. The mechanical performance of wood depends on its microscopic structure (shape and size of tracheids), submicroscopic structure (layered structure of the cell wall and distribution of fundamental chemical compounds in the wall), the occurrence of defects and the wood density (packing of wood substance in a unit volume), moisture content and temperature. The inter- and intraspecific differences in wood structure are responsible for variations in the wood mechanical performance in a rather wide range. Despite these considerable variations, wood is a valuable construction material because of highly desirable values of the strength/density index.

Traditionally, the quality of wood, both as a raw product and construction material, is evaluated on the basis of its density (Bunn 1981, Bamber and Burley 1983). In oven-dry wood the density reflects the packing of wood substance in a unit volume. The density of wood is a rather complex parameter. Its value depends on the quantitative ratios of the cells making the conductive and reinforcing tissue, and more exactly on the widths of cell walls and lumen areas and their chemical composition. The packing of cell walls in the bulk wood tissue is expressed by the so-called relative density defined as the ratio of the oven-dry wood density (ρ_0) to the density of wood substance (ρ_{ws}) (ρ_0/ρ_{ws}) (Gibson and Ashby 1997). However, the quality of wood substance of which the cell walls are built is not constant despite the practically unvaried density. The observed changes in quality are related to the changes in the content of fundamental chemical compounds (cellulose, hemicelluloses, lignin) and their distribution in particular layers of the cell wall. Cellulose appearing in the form of microfibrils, in which the crystalline areas are characterised by great rigidity in the direction parallel to their axes, is responsible for the strength and rigidity of cell walls in the longitudinal direction.

The arrangement of microfibrils in individual layers of the cell wall is optimum from the point of view of the mechanics of a growing tree (Cave and Walker 1994). The thickest cell wall layer is denoted as S2. It makes from 79 to 86 % of the width of the whole wall (Fengel and Stoll 1973) and determines the properties of wood. In wood from coniferous species with growing maturity of the wood tissue, the mean microfibril angle (MFA) value in S2 decreases (Preston and Wardrop 1949, Donaldson 1998, Sahlberg et al. 1997), while the density of wood increases (Zhang 1998, Alteyrac et al. 2006). The two above mentioned parameters show the most pronounced variations in the juvenile tissue. Therefore, the mature wood (farther from the pith) has much better mechanical properties than the juvenile one. The length of the juvenile growth of trees depends – besides the genetic conditions – also on the position of a tree in a tree stand (Zobel and Buijtenen 1989).

It is reasonable to suppose that upon external loading applied along the grain and assuming constant density of wood substance and invariable wood quality, the mechanical strength of the bulk wood tissue should be similar to that of the cell walls calculated taking into account the cells' packing in the bulk wood cross-section. However, the results of the studies reported by many authors (Raczkowski 1965, Dinwoodie 2000, Moliński and Raczkowski 1993, Zhang 1997) have shown much greater increase in the wood strength than that implied by its density. Therefore, wood density is not the only one determinant of its mechanical properties. Walker and Woollons (1998). Bendtsen and Senft (1986) and Cave and Walker (1994) claim that the most important factor determining the mechanical properties of wood in the longitudinal direction is the MFA in S2 layer of the secondary cell wall. Earlier Cave (1968) has shown that the rigidity of the cell wall increases 5 times at the mean MFA decrease from 40 to 10°. The above observation has been confirmed in later studies of the mechanical strength and modulus of elasticity of cell walls and is commonly accepted now (Cave 1976, Cave and Walker 1994, Reiterer et al. 1999, Groom et al. 2002a and b, Moliński and Krauss 2008). Moreover, Reiterer et al. (1999) have shown that the mechanical strength of cell walls of earlywood and latewood tracheids of spruce tree (*Picea abies*) and their elasticity moduli determined by testing the tensile strength along the grain on microtome samples , take the same values if the MFA values in these cells are the same. The same authors have also proved that with increasing MFA the break patterns are more distorted. The results reported by Sedighi-Gilani and Navi (2007) for single tracheids did not confirm such direct relations but the tendencies of changes were the same. As the MFA can take significantly different values even in the neighbouring tracheids (its values in the radial and tangential walls are different), (Lichteneger et al. 1999, Wang et al. 2001. Anagnost et al. 2002, Fabisiak and Moliński 2007a and b), the deformation of bulk wood in the axial direction produces highly inhomogeneous stress distribution, and as a result the process of wood destruction takes place in stages. This study was undertaken to establish the differences in the tensile strength and elasticity modulus of wood and cell walls in early and latewood of pine (*Pinus sylvestris* L.) determined by testing the tensile strength along the grain, as a function of the cambial age of annual rings.

MATERIAL AND METHODS

Mechanical parameters of earlywood and latewood were determined on material from a pine tree from the class of dominant tress in an even-aged 62-year old forest stand. The tree was characterised by a cylindrical straight stem and a symmetrically spreading crown. The stem diameter at a height of 1.3 m was 32 cm, while its height was 24.5 m. The tree was cut down, at the breast height. A block was cut out with a length of about 70 cm, from which a central balk of 60 mm in thickness was cut out. The balk was sawed along the pith and from its northern part a plank of 13 mm in thickness was cut out so that the annual rings were tangent to its thickness. The plank was subjected to planing to reduce its thickness in the tangent direction to 10 mm. From its front surface a strip of about 7 mm in thickness was cut off to be used for macrostructural measurements and for MFA measurements in the tangent walls of tracheids. From the remaining part two sections of 12 cm in length were cut off in such a way as to comprise the whole northern radius of the tree in which the annual rings were parallel to their length. Later, they were plasticized by boiling in distilled water for about 35 h. At the next stage, the tangent-oriented samples of the radial thickness of about 200 μm were sliced from the earlier selected annual rings, using sliding microtome. The samples were arranged in the sequence of slicing on a filtration tissue and labelled in the way permitting identification of their position in the annual ring. The number of samples depended on the ring's width (up to 20). The sets of samples prepared in this way were conditioned under laboratory conditions (t = 21°C, RH = 33 – 41 %) until they reached equilibrium moisture content. After the mass of the samples got stabilised, the widths of the samples were measured on an increment meter BIOTRONIK to an accuracy of 0.01 mm, and their thicknesses were measured by a micrometer screw to an accuracy of 0.001 mm at the centre of their length and at about 2 cm from the centre. The lengths of the samples were measured by a measuring rule. Each sample was weighed on a laboratory balance to the accuracy of 0.001 g and the density of each sample was calculated.

Prior to the tensile strength test, the ends of the samples were strengthened with hardboard (3 mm thick, 20 mm wide) protecting them against destruction in the testing machine. The tensile strength test was performed on a testing machine ZWICK ZO50TH using an extensometer BTC-EXMARCO.001 for measurements. The testing machine was connected with a PC unit loaded with samples dimensions. The sample was stretched at a rate of 0.5 $mm.min^{-1}$. The correct results were those obtained for the samples broken more or less at the mid length.

The stripe of wood in which the widths of annual rings and contributions of latewood had been measured was now divided into three fragments. Each of them was heated in a 20 % of $Cu(NO_3)_2$ solution in a heat bath at 80°C for 24. This process permitted visualisation of the course of microfibrils in the walls of tracheids. From the annual rings from which the samples for tensile strength tests were cut off, the tangent microscopic preparations were made having a the thickness close to 20 μm. In these preparations the microfibril angle was measured in the tangential walls of tracheids with the use of the computer image analyser. From a single annual ring the preparations were sliced more or less at every 0.5 mm. After the preparation slicing, its position in the annual ring was established by a Brinell magnifying glass and noted. In each preparation 20 MFA were measured. A scheme of preparation of the samples for tensile strength tests and for MFA observations is shown in Fig. 1.

The tensile strength and modulus of elasticity values obtained from the tests were expressed as the tensile strength of the cell walls (TS c.w.) and elasticity modulus of the cell walls (MOE c.w.) with the help of the following formulae:

$$TSc.w = \text{TS}\frac{1500}{\rho}$$

$$MOEc.w = \text{MOE}\,\frac{1500}{\rho}$$

where: 1500 – density of the wood substance ($kg.m^{-3}$)
TS – tensile strength of the wood (MPa)
MOE – elasticity modulus of the wood (GPa)
ρ - density of wood in individual samples ($kg.m^{-3}$)

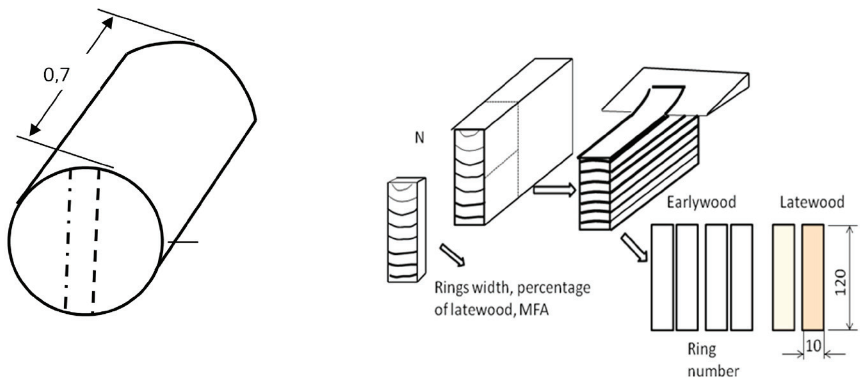

Fig.1: Schematic presentation of sample preparation

RESULTS AND DISCUSSION

The values of density of wood determined in individual zones of the annual rings studied are given in Fig. 2. These values were obtained for the typical earlywood or latewood zones, disregarding those from the intermediate zones. From the obtained results it follows that the density of earlywood decreases with the increasing cambial age of annual rings. This decrease is observed in the first near-pith rings, in the juvenile tissue. The density of the mature wood gets stabilised at a constant level within the range of 200 and 300 $kg.m^{-3}$. The decrease in the earlywood density in the juvenile tissue is related to increasing radial size of the tracheids. The same tendency of decreasing density in earlywood has been reported for the other tree species, *Tsuga heterophylla* (Panshin et al. 1964), *Picea mariana* (Zhang 1998) and *Larix kaempferi* (Koizumi et al. 2005). The density of latewood clearly increased with the increasing cambial age up to about annual ring 20. In ring 4, its value was 365 $kg.m^{-3}$, which was by about 16 % higher than the mean density of earlywood of 315 $kg.m^{-3}$, while in ring 20, the mean density of latewood was 697 $kg.m^{-3}$ and was 2.7 times greater than that of earlywood in the same ring (258 $kg.m^{-3}$). In farther annual rings the difference in the densities of the early and latewood only slightly increases. Assuming that the above differences in wood density correspond to the cyclic inhomogeneity of wood (Raczkowski 1965), it can be concluded that the juvenile wood shows lower inhomogeneity than the mature tissue. The changes in the latewood density with increasing cambial age can be a good criterion for determination of the border between the juvenile and mature zones in a cross-section of a tree. In the dominant pine tree studied, the period of juvenile growth can be estimated as about 20 years. Moreover, the results imply that the increase in the density of the bulk wood tissue along the tree stem radius is a consequence of increasing density of latewood.

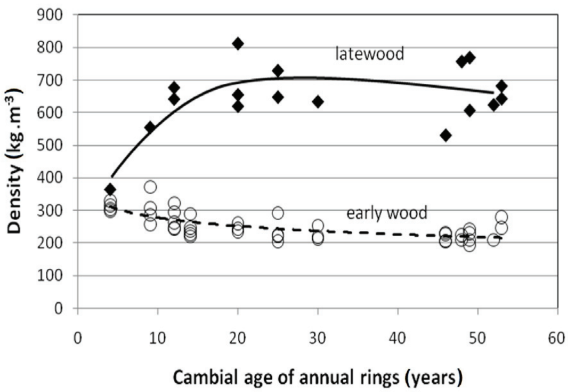

Fig. 2: The early- and latewood density versus the cambial age of annual rings

Results of the tensile strength measurements along the grain and the modulus of elasticity values are given in Fig. 3. According to these data the tensile strength of earlywood slightly increases with the cambial age of the annual rings; its average values are 29 MPa in ring 4 and 35 MPa in ring 50, although the density of the same wood decreased with increasing cambial age; its average values were ~300 $kg.m^{-3}$ in ring 4 and 210 $kg.m^{-3}$ in ring 50. The mean value of the modulus of elasticity of earlywood practically does not change up to about ring 30, its mean values is ~ 4500 MPa, and then decreases to about 3500 MPa in ring 50. In latewood the tensile strength significantly increases up to ring 20 and in the subsequent rings its increase is very small. It is worth noting that in ring 4 the tensile strength of latewood of about 35 MPa, was only by 20 % greater than the mean tensile strength of the earlywood in the same ring. In this ring the differences in the tensile strength of the early and latewood were correlated with the differences in their densities. Starting from ring 20, the tensile strength of latewood (varying from 123 to 200 MPa; mean value of 155 MPa) was almost 4 times greater than that of earlywood (40 MPa). The elasticity modulus of latewood varies with the cambial age of annual rings in the same way as its tensile strength. For latewood in ring 4, the elasticity modulus was 5330 MPa, which was by only 18 % greater than the mean value of the modulus for earlywood in this ring. The mean elasticity modulus for the latewood in ring 20 was 15600 MPa, which was 3.4 times higher than for the earlywood in the same ring (4542 MPa).

Changes in the elasticity modulus of latewood along the tree stem radius are more pronounced than those in the wood density. The latewood density in ring 4 was 365 kg.m^{-3} and in ring 49 it was 688 kg.m^{-3}. It increased 1.88 times, whereas the mean value of the modulus of elasticity increased from 5330 MPa in ring 4 to 21 440 MPa in ring 49, 4 times. Thus, the increase in MOE of latewood along the tree stem radius was over twice greater than the increase in the wood density. These results fully confirm the earlier observations, reported by Cave and Walker (1994), that the wood density cannot be treated as a universal and reliable indicator of the wood mechanical performance. It can be concluded however, that the changes in wood density within individual annual rings contributed to a substantial scatter of the mechanical parameters of the wood.

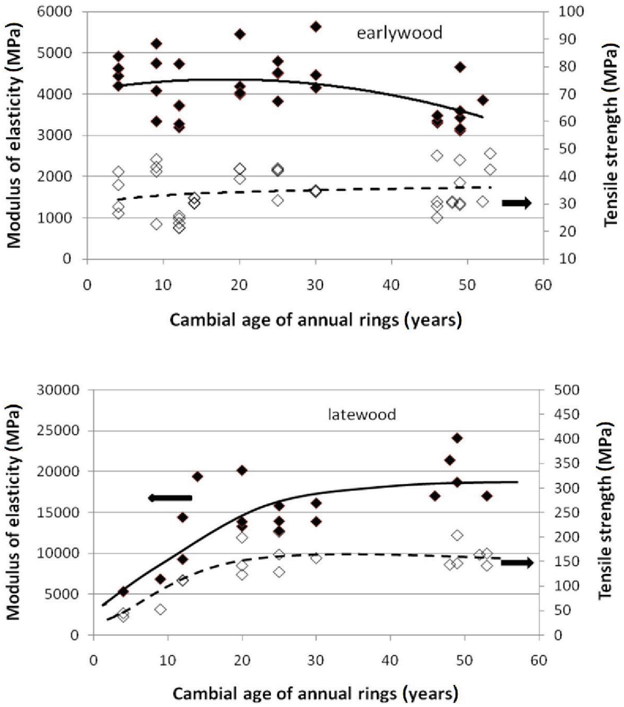

Fig. 3: Tensile strength and modulus of elasticity of early- and latewood versus the cambial age of annual rings

The tensile strength and elasticity modulus values calculated for the cell walls of tracheids are presented in Fig. 4 as a function of the cambial age of the annual rings, separately for earlywood and latewood. The figure shows the elasticity modulus values calculated only for the samples for which the mean MFA value could be determined from the measurements in microscopic preparations. As follows from the data presented, the strength of the cell walls of late tracheids is greater than that of early ones. The mean tensile strength of cell walls from early tracheids varies from 150 MPa in ring 4 to 250 – 260 MPa in ring 20 and father. In late tracheids the mean tensile strength in the juvenile wood increases from 180 MPa in ring 4 to about 330 MPa in ring 20 and remains more or less at this level in farther rings. For both types of tracheids the tensile strength of cell walls varies significantly within individual rings.

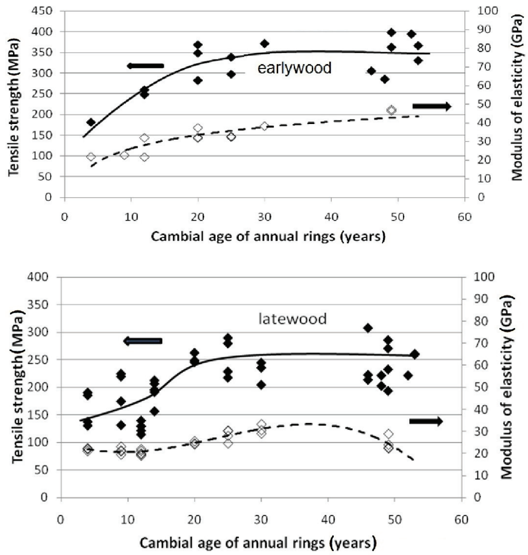

Fig. 4: Tensile strength and modulus of elasticity of cell walls versus the cambial age of annual rings

The modulus of elasticity is also variable. In early tracheids it varies from 21.2 GPa in ring 9 to 31 GPa in ring 30, then it decreases to reach 23 GPa in ring 49. In late tracheids the elasticity modulus increases from 23 GPa for late tracheids from ring 4 to 46.6 GPa for those in ring 49. The main factor responsible for the changes in the modulus of elasticity is MFA. This fact is clearly illustrated in Fig. 5, presenting changes in the mean values of the elasticity modulus of call walls versus the cambial age of annual rings, calculated separately for early and latewood tracheids, and the corresponding mean MFA values also versus the cambial age of rings. The tendencies of changes in the Young modulus and MFA versus the cambial age of annual rings are practically the mirror reflections; the Young modulus of cell walls increases when MFA decreases. The correlation between these two parameters presented in Fig. 6, for the MFA range considered can be approximated by a linear function of high coefficient of determination, similarly as the correlation between the tensile strength of the cell walls and MFA. Therefore, the main factor responsible for the variation in the modulus of elasticity and tensile strength of the cell walls within individual annual rings and with their cambial age is the value of MFA, especially in S2 layer. Our results have confirmed the earlier reports (Cave and Walker 1994, Reiterer et al. 1999, Groom et al. 2002). Taking into account significant variation in MFA in different tracheids of the wood studied in the tangential preparations (Fabisiak et al. 2008), the correlation between the parameters characterising mechanical performance of cell walls and MFA should be treated as very high.

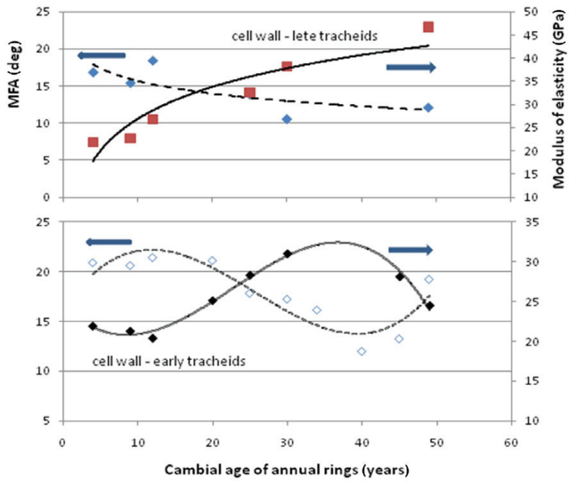

Fig. 5: Radial variation in the modulus of elasticity of cell walls and MFA of early- and latewood

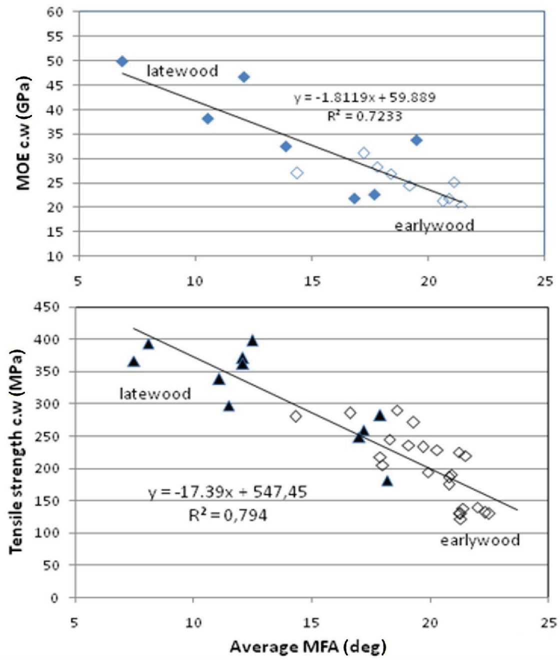

Fig. 6: Relation between the modulus of elasticity and tensile strength of cell walls in early and latewood and the microfibril angle

Fig. 7 shows the indices of cyclic inhomogeneity, defined as the quotients of the mean values of parameters for the late and early wood, as a function of the cambial age of the annual rings. The index of cyclic inhomogeneity defined as the quotient of the tensile strength of latewood (TS_{lw})

to that of earlywood (TS_{ew}) is noted to take higher values than that calculated on the basis of the quotient of the latewood density to that of earlywood (ρ_{lw}/ρ_{ew}), which confirms the earlier observations. These two indices, (TS_{lw})/ TS_{ew}) and (ρ_{lw}/ρ_{ew}), increase with growing cambial age of annual rings. The variation in the tensile strength of cell walls in late and earlywood within individual annual rings ($TS_{cw} = TS_{clw}/TS_{cew}$) also increases with growing cambial age, but only to about ring 30, which is related to the differences in changes in the ratio of the MFA in late tracheids (MFA_{lw}) to that in early tracheids (MFA_{ew}). The product of the earlier defined inhomogeneity indices: (TSc_{lw}/TS_{cew}) x (MFA_{lw}/ MFA_{ew}) is close to unity for all annual rings studied.

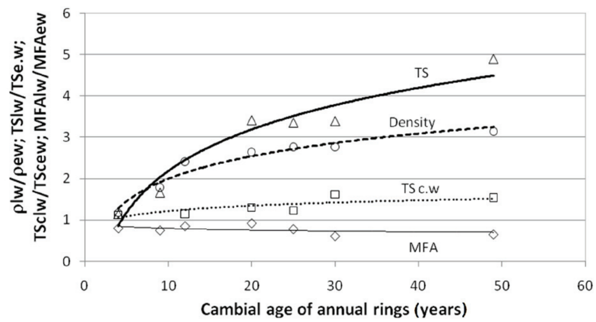

Fig.7: Indexes of inhomogeneity versus cambial age of annual rings

On the basis of the above presented results it was possible to analyse the tensile strength of wood as a function of the tensile strength of cell walls. Fig. 8 presents the tensile strength of the early and latewood versus the tensile strength of the cell walls.

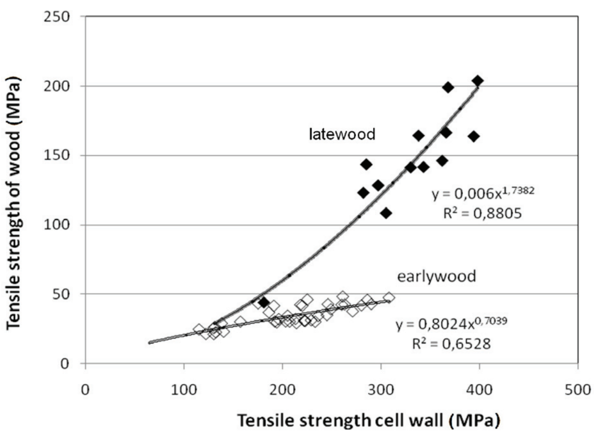

Fig.8: Relationship between tensile strength of early- and latewood and tensile strength of cell walls

According to the plots, the influence of the cell wall strength on the wood strength is much lower for early than for late tracheids. The mean tensile strength of early wood, as it follows from Fig. 3, increases with the cambial age, while the wood density decreases, see Fig. 2. Thus, it can be concluded that the tensile strength of earlywood is fully determined by that of cell walls, while the tensile strength of latewood depends on that of the cell walls and on their packing, that is on the wood density. Assuming that the relation between the tensile strength of latewood and that of cell walls is well described by a power equation, the increase in the tensile strength of cell walls from 200 to 400 MPa (2 times) corresponds to the wood tensile strength increase by about 3.3 times, from 60 to 200 MPa. Thus, the increase in the tensile strength of latewood is in 60 % (2/3.3 = 0.606) determined by the increase in the tensile strength of the cell walls and in 40 % by the wood density.

CONLUSIONS

The conclusions following from analysis of the above presented evidence are given below.

1. In the juvenile tissue, the earlywood density decreases and the latewood density increases. In the mature wood (from ring 20 onwards) the densities of both zones stabilise. With the increasing maturity of wood tissue its cyclic inhomogeneity increases.

2. The tensile strength and the modulus of elasticity of earlywood are practically independent of the cambial age of annual rings. For latewood the values of these parameters increase with growing cambial age of the rings up to about ring 20. In the first near-pith annual rings the differences in the mechanical parameters between earlywood and latewood are about 20 %, while in the mature tissue these differences are almost fourfold.

3. The mean tensile strength of cell walls of early tracheids varies from 150 MPa in ring 4 to 250 – 260 MPa in ring 20 and farther. The mean tensile strength of cell walls of late tracheids in the juvenile zone increases from 180 MPa in ring 4 to about 330 MPa in ring 20, and remains more or less the same for farther rings.

4. The Young modulus of cell walls in early tracheids varies from 21 GPa to 31 GPa, while in late tracheids it increases with growing cambial age of annual rings from 23 GPa to 46.6 GPa. The main factor responsible for so significant differences in the Young modulus between early and late tracheids is the microfibril angle. The relation between the Young modulus and MFA in the range studied can be approximated by a linear equation of a high coefficient of determination (R2 =0.723).

5. The tensile strength of earlywood is fully determined by that of cell walls. The tensile strength of latewood is in 60 % determined by the tensile strength of the cell walls and in 40 % by wood density.

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Andrzej Krauss, Waldemar Moliński
Poznań University of Life Sciences
Faculty of Wood Technology
Wojska Polskiego 38/42
60-627 Poznań
Poland
Corresponding author: akrauss@inet.com.pl

Jozef Kúdela, Igor Čunderlík
Technical University in Zvolen
Faculty of Wood Science
T.G. Masaryka 24
960 53 Zvolen
Slovak Republic