

# COMPRESSIVE STRENGTH PARALLEL TO GRAIN OF EARLYWOOD AND LATEWOOD OF YELLOW PINE

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## ABSTRACT

The compressive strength parallel to grain of earlywood and latewood from the yellow pine sapwood and heartwood areas was examined in the study. The structure of the basic anatomical elements of wood tracheids, which conduct water and/or perform the mechanical function - was also characterized. The compressive strength parallel to grain of latewood in the sapwood area was found to be twice as high as the compressive strength parallel to grain of earlywood. The compressive strength parallel to grain of latewood in the heartwood area, on the other hand, was found to be 2,5 times higher than the compressive strength parallel to grain of earlywood. This was due to the density of particular areas of wood and the dimensions of structural elements - tracheids. In the sapwood area, the density of latewood was ca. twice as high as the density of earlywood. Similar relationships were found for heartwood. The thickness of latewood tracheids was found to be 1,5 times greater than the thickness of earlywood tracheids. These relationships were observed in sapwood and heartwood. The diameter of earlywood tracheids in radial direction was twice as large as the diameter of latewood tracheids. These relationships were observed in yellow pine sapwood and heartwood.

**Keywords:** Anatomy, compressive strength, earlywood, fibre, latewood, *Pinus ponderosa*, tracheids.

## INTRODUCTION

Yellow pine (*Pinus ponderosa*) is the most commonly found pine species in North America (FNA 1993). Trees grow up to 72 m in height, while the trunk can reach up to 2,5 m in diameter. It is a species with a significant economic importance. Yellow pine is commonly used for the production of construction materials. In the case of these types of materials, it is important for them to be characterized by appropriate mechanical properties. Alongside bending strength, compressive strength parallel to grain is one of the most frequently used strength tests (Wagenführ 2007, ISO 13061-17/2017). This is largely due to the fact that most construction materials made of wood are subjected to bending and/or compression. Compressive strength parallel to grain varies significantly depending on the wood species, density, moisture content, anatomical structure, annual ring width, share of latewood, wood defects (Wagenführ 2007, Kretschmann 2010). The age of the trees from which sample material for testing is obtained is also important (Listyanto 2018).

In the case of softwood, the differences in structure between earlywood and latewood within a single annual growth ring can be observed organoleptically. It is often the case, particularly in heavily managed plantations, that the density of wood in softwood species diminishes as the width of rings increases (Tasissa and Burkhart 1998). It should be noted, however, that even wood with a regular annual growth ring pattern, without defects, is characterized by an internal heterogeneity of structure. An effect of this heterogeneity is considerable density fluctuations, at a level of several hundred kg/m<sup>3</sup>. This translates directly into the

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physical and mechanical properties of wood. Kretschmann and Cramer (2007) investigated the change in average specific gravity at various rings and heights for earlywood and latewood of loblolly pine. The specific gravity of earlywood determined for a tree up to the 21<sup>st</sup> annual growth ring changed slightly, from 0,25 to 0,35. The specific gravity of latewood in the 3<sup>rd</sup> annual growth ring ranged from 0,4 to 0,5. It was found that latewood specific gravity increased rapidly between rings 3 and 6, and then increased more gradually with increasing distance from the pith. In the 21<sup>st</sup> annual growth ring, the specific gravity of latewood was 0,7. The climate, diverse seasons, the length of the growing season, as well as the level of precipitation determine the width of annual growth rings. Long-term changes in temperature result in a change in the width of annual growth rings (Olivar *et al.* 2015).

The physical and mechanical properties of wood are determined with the use of samples of various sizes. Tests are often conducted on full-size sawn wood and on small defect-free specimens. Tests conducted on very small samples, enabling the determination of the impact of the structure of the annual growth ring on wood properties, are carried out increasingly frequently. Zink-Sharp and Price (2006) found that an understanding of intra-ring mechanical properties is required for complete characterization of the interrelationships within wood's hierarchical structure. The authors determined intra-ring compression strength parallel to the grain for small samples (a few millimeters<sup>3</sup> in volume) of sweetgum, yellow-poplar, and red maple. Zhang *et al.* (2010) determined the yield stress and compressive strength of, among others, the wood of loblolly pine (*Pinus taeda*) with the use of cylindrical-shaped micro-pillars cut from a cell wall. Hein and Lima (2012) evaluated the correlation between the microfibril angle (MFA) and the modulus of elasticity in compression parallel to grain and compressive strength using juvenile wood of *Eucalyptus grandis* from fast-growing plantations. Cramer *et al.* (2005) measured the elastic properties of the earlywood and latewood of loblolly pine by using specimens of 1 mm × 1 mm × 30 mm.

There is no sufficient data about the relation between the anatomy and mechanical properties of yellow pine in available literature. Furthermore, there is no universally accepted testing regime for determining the micro-mechanical properties of wood samples (Zink-Sharp and Price 2006). Therefore, the objective of this paper was to supplement the knowledge about the relation between the anatomy and compressive strength parallel to grain of the earlywood and latewood of yellow pine depending on the wood area (sapwood, heartwood). The basic microstructural elements, i.e. tracheids of yellow pine wood, were measured in terms of the thickness and diameter of walls in radial and tangential directions.

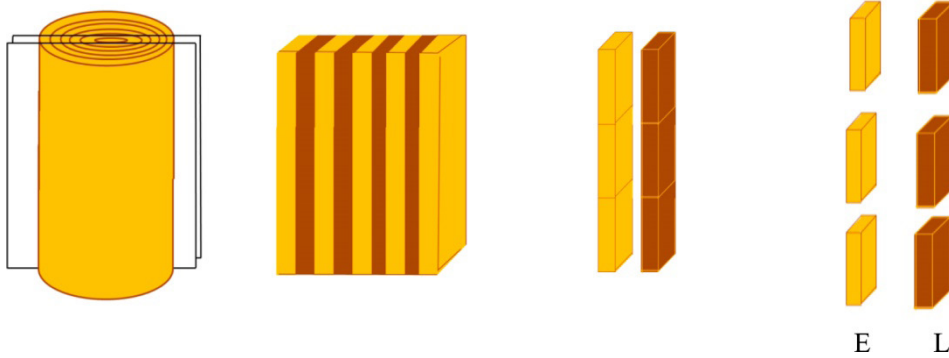
## MATERIALS AND METHODS

Samples of yellow pine wood (*Pinus ponderosa* Douglas ex C. Lawson) coming from the western part of the USA were used for the study. The study subject was yellow pine wood about 70 years old. The wood was provided in the form of air-dry sawn wood with a thickness of 30 mm (radial), width of 300 mm (tangential) and length of 1500 mm (longitudinal). Five boards were used for preparing test specimens (each from a different tree). The surface of the sawn wood was finished by planing. The samples were obtained from a knot-free butt-end part. Equal groups of samples were obtained from the sapwood and heartwood areas of the sawn wood. Wood moisture content was determined according to ISO 13061-1 (2014). The density of yellow pine wood was determined using the stereometric method, as required under ISO 13061-2 (2014).

### Testing compressive strength parallel to grain

Compressive strength parallel to grain (CS) was determined for yellow pine wood from the sapwood (S) and heartwood (H) areas. The CS tests of yellow pine were carried out in accordance with ISO 13061-17 (2017), using standard samples. 30 samples were used for testing CS of the yellow pine sapwood and heartwood.

The compressive strength parallel to grain of earlywood (E) and latewood (L) from the yellow pine sapwood and heartwood areas was determined. Samples with the dimensions 5 mm (tangential) × 10 mm (longitudinal) were used in this case. The thickness of the samples (measured in radial direction) corresponded to the width of earlywood or latewood within a single annual growth ring in particular areas (sapwood, heartwood). The scheme for obtaining samples for testing the CS of earlywood and latewood is presented in Figure 1. The CS of earlywood and latewood from sapwood and heartwood were determined according to ISO 13061-17 (2017).



**Figure 1:** The preparation process of the earlywood (E) and latewood (L) test specimens.

The tests of compressive strength parallel to grain were carried out by using a computer program coupled with Instron® testing machine, model 3382 (Norwood, USA). The wood properties were determined for 30 samples of each variant (sapwood\_earlywood - S\_E, sapwood\_latewood - S\_L, heartwood\_earlywood - H\_E, heartwood\_latewood - H\_L) of the CS measurement of yellow pine wood.

#### Determination of the average width of annual growth rings

Annual growth rings were measured on samples with the dimensions corresponding to the entire cross-section for testing compressive strength parallel to grain (with the use of standard samples according to ISO 13061-17 (2017)). The measurement was carried out along the line marking the radial direction. All full annual growth rings in the sample were measured. The average width of annual growth rings was determined with the use of a LINTAB™ 5 tree-ring measurement station (RINNTECH, Heidelberg, Germany). The measurement consisted in determining the length of the measurement section and counting the number of annual growth rings in the measurement section. The average width of annual growth rings was calculated in accordance with Equation 1:

$$RW = \frac{l}{n} (mm) \quad (1)$$

Where: RW - the average width of annual growth rings (mm),

l - the length of the measurement section (mm),

n - the number of annual growth rings in the measurement section.

#### Determination of the share of latewood

The widths of the earlywood and latewood areas (with accuracy to 0,01 mm) were determined in the measurement section with the use of a LINTAB™ 5 tree-ring measurement station (RINNTECH, Heidelberg, Germany). The share of latewood was calculated in accordance with Equation 2:

$$SL = \frac{LW}{EW + LW} \times 100(\%) \quad (2)$$

Where: SL - the share of latewood (%),

EW - the earlywood width in the measurement section (mm),

LW - the latewood width in the measurement section (mm).

### Microscopic preparations and the measurement of tracheids

Samples of yellow pine with the dimensions 10 mm (radial) × 10 mm (tangential) × 10 mm (longitudinal) were used for making microscopic preparations. The samples were obtained from boards prepared for testing, separately from sapwood and heartwood areas. The wood samples were soaked for a month in a solution of water, glycerin and 96 % ethyl alcohol (1:1:1 volume ratio). 15 μm - 20 μm thick preparations were cut with the use of a sledge microtome (Reichert, Vienna, Austria). Preparations were stained with 5 % safranin solution in 96 % ethyl alcohol.

The microscopic observation and measurement were carried out with the use of an Olympus BX41 microscope (Olympus Corporation, Tokyo, Japan) with a digital camera and the Cell B software. The anatomical elements of wood were measured in transverse section images. The following parameters of earlywood and latewood tracheids were measured: thickness of radial and tangential walls, diameter in radial and tangential directions. 30 measurements were taken for each parameter of tracheids under examination.

### Statistical analysis of study results

The statistical analysis was performed using the STATISTICA (StatSoft 2013). The statistical analysis of the results was carried out at a significance level of 0,050.

## RESULTS AND DISCUSSION

The average density of yellow pine sapwood (S) and heartwood (H) was (with the determined moisture content of 8 % - 10 %), respectively, 535 kg/m<sup>3</sup> (± 75 kg/m<sup>3</sup>) and 657 kg/m<sup>3</sup> (±88 kg/m<sup>3</sup>) (Figure 2a) and the differences were statistically significant (t-test,  $p \leq 0,050$ , Table 1). From data available in literature it can be seen that the average density of yellow pine wood with a moisture content of 12 % - 15 % ranges from 340 kg/m<sup>3</sup> to 500 kg/m<sup>3</sup> (Wagenführ 2007). These density values are lower than those recorded in the yellow pine tests. The differences may be due to a number of factors, such as e.g. habitat conditions (Peltola *et al.* 2009, Traoré *et al.* 2018).

The density of earlywood in the heartwood area (H\_E) was 432 kg/m<sup>3</sup> (± 65 kg/m<sup>3</sup>) and was 28 % greater than the density of earlywood in the sapwood area (S\_E), for which the value of 338 kg/m<sup>3</sup> (± 40 kg/m<sup>3</sup>) was recorded (Figure 2a). By contrast, the density of latewood in the heartwood area (H\_L) was 872 kg/m<sup>3</sup> (± 95 kg/m<sup>3</sup>) and was 38 % greater than the density of latewood in the sapwood area (S\_L), for which the value of 633 kg/m<sup>3</sup> (± 37 kg/m<sup>3</sup>) was recorded. The indicated relationships were statistically significant (t-test,  $p \leq 0,050$ , Table 1).

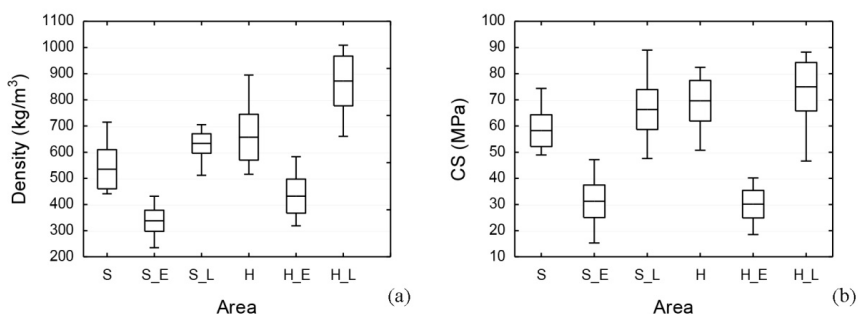


Figure 2: (a) Density and (b) compressive strength (CS) parallel to the grain of yellow pine.

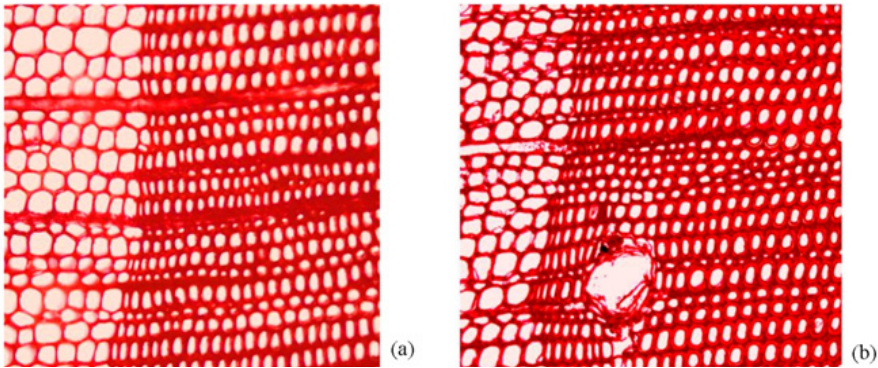
**Table 1:** Statistical analysis of yellow pine density and CS test results.

Area	Properties			
	Density		CS	
	Statistical measures			
	t	p	t	p
S vs. H	-8,6518	0,000000	-8,6708	0,000000
S_E vs. S_L	-46,1958	0,000000	-32,1251	0,000000
S_E vs. H_E	-10,6312	0,000000	0,9830	0,327131
S_L vs. H_L	-16,5855	0,000000	-4,6151	0,000014
H_E vs. H_L	-22,4989	0,000000	-25,1168	0,000000

Compressive strength parallel to grain (CS) determined in standard size samples was as follows: 58 MPa ( $\pm 6$  MPa) for sapwood (S) and 70 MPa ( $\pm 8$  MPa) for heartwood (H) (Figure 2b), and the differences were statistically significant (t-test,  $p \leq 0,050$ , Table 1). The lower CS of sapwood could be attributed to the lower density of sapwood compared to heartwood. From data available in literature it can be seen that the CS of yellow pine wood ranges from 28 MPa to 43 MPa (Wagenführ 2007). Much lower literature values are due to the fact that they presumably refer to the averaged sapwood and heartwood values for yellow pine. Variability in CS may also be due to differences in wood density caused by, among other things, habitat conditions (Peltola *et al.* 2009, Traoré *et al.* 2018).

The CS of earlywood in the sapwood area (S\_E) was similar to the CS of earlywood in the heartwood area (H\_E) and was, respectively, 31 MPa ( $\pm 6$  MPa) and 30 MPa ( $\pm 5$  MPa) (Figure 2b) and the differences were not statistically significant (t-test,  $p > 0,050$ ). By contrast, the CS of latewood in the sapwood area (S\_L) and in the heartwood area (H\_L) was respectively 66 MPa ( $\pm 8$  MPa) and 75 MPa ( $\pm 9$  MPa) and the differences were statistically significant (t-test,  $p \leq 0,050$ , Table 1). In general, it can be concluded that the CS of the S\_E wood was half the value of the CS determined for sapwood, using standard samples. Similar relationships were found in the case of heartwood, i.e. the H\_E value was half the CS value determined for heartwood determined with standard samples. The CS determined for S\_L and H\_L, on the other hand, was similar to the CS value determined for, respectively, sapwood and heartwood (for standard samples). A cell wall has much higher compressive strength. Zhang *et al.* (2010) demonstrated that the compressive strength of a loblolly pine (*Pinus taeda*) cell wall was 125 MPa. Büyüksarı *et al.* (2017) observed that the difference in the mechanical properties of earlywood and latewood of Scots pine could be attributed to the differences in density and microfibril angle (MFA) of earlywood and latewood. Roszyk (2014), when examining Scots pine wood, demonstrated that the average density of earlywood and latewood was, respectively, 235 kg/m<sup>3</sup> and 665 kg/m<sup>3</sup>, whereas the MFA was, respectively, 16,4 ° and 9,0 °. In the small MFA, the cellulose determined wood properties, whilst with increased MFA, the mechanical properties of cell walls became more dependent on the matrix (hemicelluloses, lignin) incrusting the cellulose skeleton (Bergander and Salmén 2002, Barnett and Bonham 2004, Roszyk *et al.* 2016, Büyüksarı *et al.* 2017).

The width of annual growth rings in the sapwood and heartwood areas of yellow pine was, respectively, 5,73 mm ( $\pm 0,38$  mm) and 5,78 mm ( $\pm 0,56$  mm) and the differences were not statistically significant (t-test,  $p > 0,050$ ). The share of latewood in the sapwood and heartwood areas of yellow pine was, respectively, 38 % ( $\pm 4$  %) and 39 % ( $\pm 3$  %) and the differences were not statistically significant (t-test,  $p > 0,050$ ). This shows that, in the case under study, the width of annual growth rings and the share of latewood did not determine the differences between the CS of yellow pine sapwood and heartwood. Williams (2010) found that wide, prominent bands of latewood are characteristic of southern yellow pines.



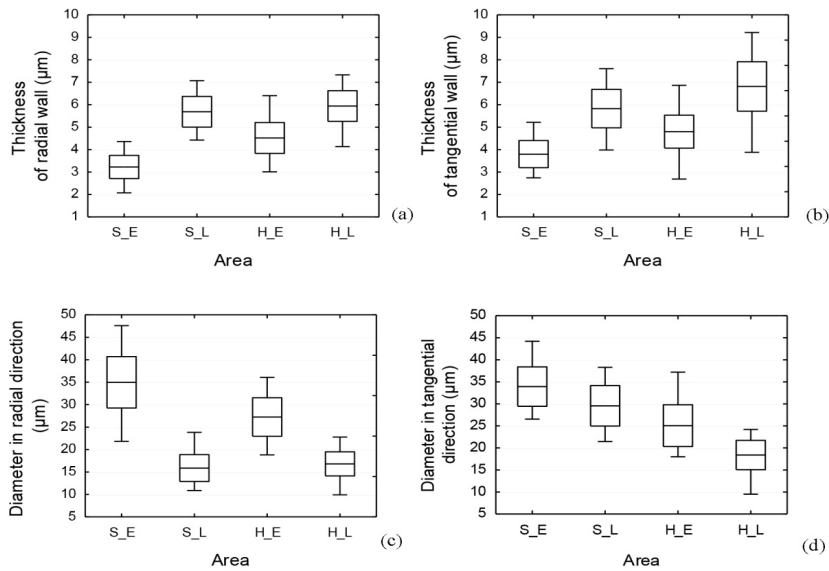
**Figure 3:** Transverse section of yellow pine (a) sapwood and (b) heartwood.

**Table 2:** Dimensions of yellow pine tracheids.

Area	Tracheids	Symbol	Dimensions			
			Thickness ( $\mu\text{m}$ )		Diameter ( $\mu\text{m}$ )	
			Radial wall	Tangential wall	Radial direction	Tangential direction
Sapwood (S)	Earlywood (E)	S_E	3,23 (0,52)	3,80 (0,60)	34,96 (5,72)	33,92 (4,46)
	Latewood (L)	S_L	5,69 (0,68)	5,82 (0,86)	15,88 (2,98)	29,55 (4,59)
Heartwood (H)	E	H_E	4,52 (0,69)	4,80 (0,74)	27,25 (4,28)	25,05 (4,74)
	L	H_L	5,94 (0,68)	6,81 (1,10)	16,81 (2,68)	18,39 (3,32)

mean and standard deviation in parentheses

Tracheids in sapwood were less thick than tracheids in heartwood (Figure 3a, Figure 3b, Table 2) which is among others, due to extractive encrustation that occurs during heartwood formation (Hillis 1999). In general, it can be observed that the thickness of latewood tracheids was 1,5 times greater than the thickness of earlywood tracheids. These relationships were observed in sapwood and heartwood. The thickness of tangential wall was greater than the thickness of radial wall (Figure 4a, Figure 4b). The greatest differences (18 %) were observed in the case of the thickness of S\_E tracheids, and the smallest (2 %) in the case of S\_L tracheids. In radial direction, H\_E tracheids were 40 % thicker than S\_E tracheids. The H\_L tracheids, on the other hand, were 4 % thicker than the S\_L tracheids. In tangential direction, H\_E tracheids were 26 % thicker than S\_E tracheids, and H\_L tracheids were 17 % thicker than S\_L tracheids (Table 2). A statistical analysis of the significance of differences between the examined dimensions of yellow pine wood tracheids was presented in Table 3.



**Figure 4:** (a) Thickness of radial and (b) tangential wall, (c) diameter in radial and (d) tangential direction of yellow pine tracheids.

**Table 3:** Statistical analysis of the significance of differences between the examined dimensions of yellow pine wood tracheids.

Area	Statistical measures			
	t	p	t	p
	Tracheids dimensions			
	Thickness of radial wall		Thickness of tangential wall	
S_E vs. S_L	22,89019	0,000000	5,285233	0,000001
S_E vs. H_E	8,358668	0,000000	10,56574	0,000000
S_L vs. H_L	-1,78918	0,076151	15,26587	0,000000
H_E vs. H_L	16,00800	0,000000	8,912603	0,000001
	Diameter in radial direction		Diameter in tangential direction	
S_E vs. S_L	22,89019	0,000000	5,285233	0,000001
S_E vs. H_E	8,358668	0,000000	10,56574	0,000000
S_L vs. H_L	-1,78918	0,076151	15,26587	0,000000
H_E vs. H_L	16,00800	0,000000	8,912603	0,000000

Tracheids in sapwood had a greater diameter than tracheids in heartwood (Table 2). The heartwood formation involves a number of physiological, anatomical, cellular, and chemical changes (Hillis 1999). Heartwood plays a mechanical role mainly. Sapwood, on the other hand, in addition to reinforcing the trunk, participates in the vital functions of the plant, i.e. mainly in conduction water and accumulating nutrients (Wilson and White 1986, Wiedenhoef 2010). The diameter of earlywood tracheids in radial direction was greater than the diameter in tangential direction, which is the opposite to what was found in latewood tracheids. This was the case both for sapwood tracheids and heartwood tracheids (Figure 4c, Figure 4d). Latewood tracheids flattened in radial direction are characteristic of softwood (Wagenführ 2007, Kozakiewicz and Życzkowski 2015). In general, it can be concluded that the diameter of earlywood tracheids in radial direction was twice as large as the diameter of latewood tracheids in this direction. These relationships were recorded in yellow pine sapwood and heartwood. In tangential direction, on the other hand, the S\_E diameter was similar to the S\_L diameter,

whereas the H\_E diameter was 36 % larger than the H\_L diameter. Among the tracheid measurements under study, the greatest variability was recorded in the case of the thickness of a tangential wall (Figure 4b), and the smallest in the case of the thickness of a radial wall (Figure 4a). The dimensions of yellow pine wood tracheids were related to density. Wood areas with tracheids with larger diameters were characterized by smaller density than wood areas with tracheids with smaller diameters. The differences were particularly noticeable between the densities of earlywood and latewood, both within sapwood and heartwood (Figure 2a).

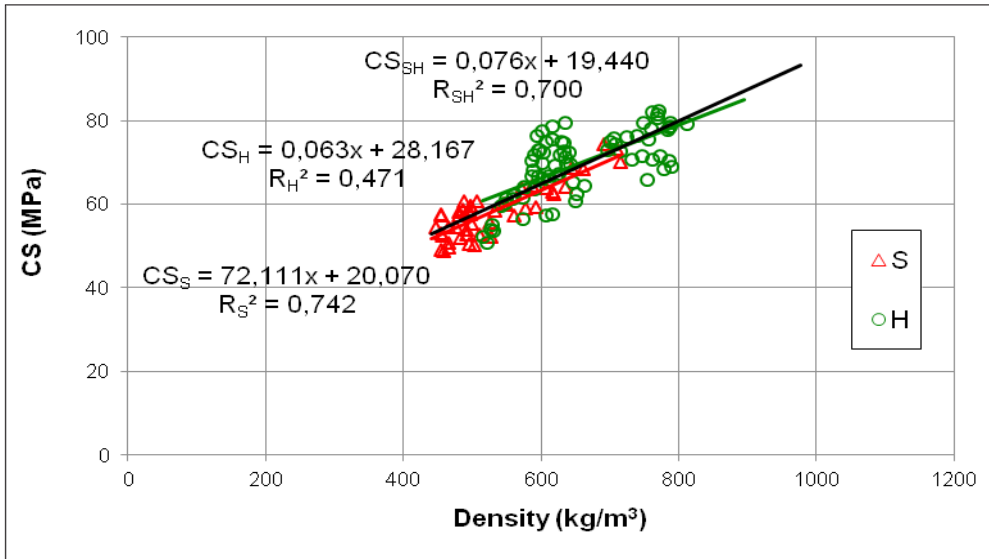


Figure 5: Compressive strength parallel to grain (CS) of sapwood (S) and heartwood (H) of yellow pine wood.

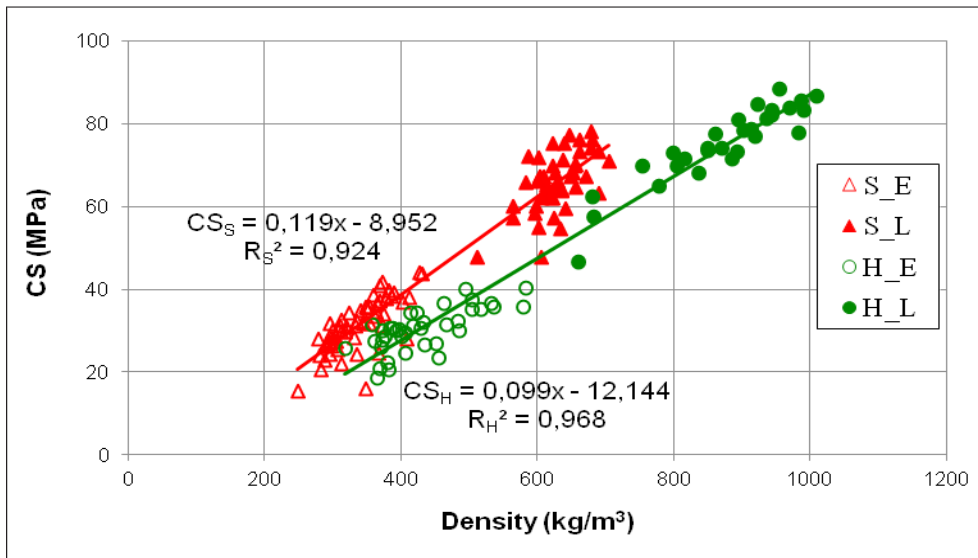
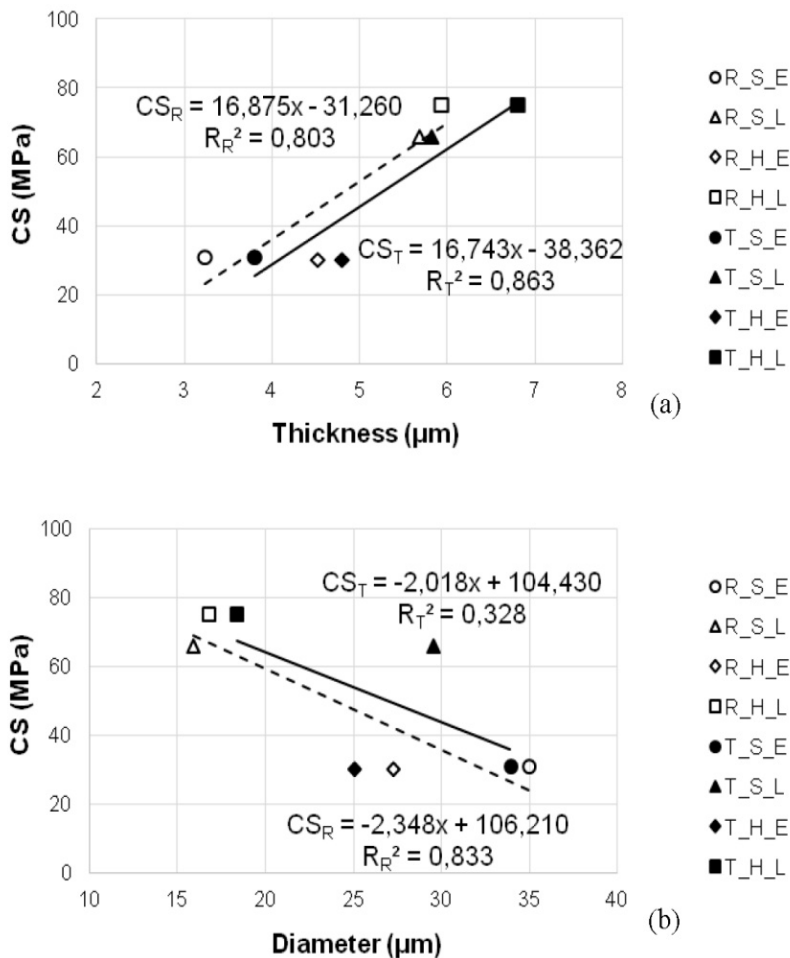


Figure 6: Compressive strength parallel to grain (CS) of earlywood (E) and latewood (L) of yellow pine in the sapwood (S) and heartwood (H) area.

Figure 5 shows the relationship between the density and the CS of yellow pine sapwood ( $R_S^2 = 0,742$ ) and heartwood ( $R_H^2 = 0,471$ ). Additionally, a linear approximation of the relationship under analysis was presented jointly for sapwood and heartwood ( $CS_{SH}$ ). The  $R^2$  ratio in this case was 0,700. Much higher values of the  $R^2$  ratio were recorded for the density - CS relationship for measurements carried out with the use of “small” samples, i.e. samples containing earlywood or latewood (Figure 6). This shows that the CS of yellow



pine wood can be “estimated” more exactly on the basis of the measurements of earlywood and latewood density. An upward trend in compression stress with increased specific gravity for intra-ring specimens taken from sweetgum, yellow-poplar and red maple was shown by Zink-Sharp and Price (2006).



**Figure 7:** Relationships between the thickness of yellow pine tracheids (a) and CS, and between the tracheids diameter (b) and CS.

The thicker the tracheid walls, the higher were the CS values of yellow pine wood (Figure 7a). The larger the diameter of tracheids, the smaller was the CS of yellow pine wood (Figure 7b). This relationship was particularly visible in the case of the impact of the diameter of tracheids measured in radial direction ( $R_R^2 = 0,833$ ). The value of the  $R^2$  ratio for relationships between the tracheid diameter measured in tangential direction and CS was 0,328. The diameter of tracheids in radial direction “determined” the CS of yellow pine earlywood and latewood to a greater extent than the diameter of tracheids in tangential direction.

## CONCLUSIONS

The compressive strength parallel to grain (CS) of yellow pine heartwood, determined in standard size samples, was 21 % higher than in the case of sapwood. This was correlated with wood density, since the average density of yellow pine heartwood was 23 % greater than sapwood density. In general, it can be concluded that the CS of earlywood in the sapwood area was half the CS value for sapwood (determined in stan-

ard size samples). Similar relationships were found in heartwood, i.e. the CS of earlywood in the heartwood area was half the CS value determined for heartwood. The CS determined for latewood in the sapwood and heartwood areas, on the other hand, was similar to the CS determined for, respectively, sapwood and heartwood. The CS of earlywood in the sapwood area was similar to the CS of earlywood in the heartwood area. The CS of latewood in heartwood area, on the other hand, was 14 % higher than the CS of latewood in the sapwood area.

No significant differences were found between the CS of earlywood in the sapwood area and the CS of earlywood in the heartwood area. The CS of latewood in the heartwood area was 14 % higher than CS in the sapwood area. It has been demonstrated that the CS of latewood in the sapwood area was twice as high as the CS of earlywood. The CS of latewood in the heartwood area, on the other hand, was found to be 2,5 times higher than the CS of earlywood. The study of microstructural elements of yellow pine showed that the diameter of earlywood tracheids in radial direction was twice as large as the diameter of latewood tracheids in this direction. The relationships applied both to yellow pine sapwood and heartwood. In sapwood, in tangential direction, the diameter of earlywood tracheids was similar to the diameter of latewood tracheids. By contrast, in heartwood, in tangential direction, the diameter of earlywood tracheids was 36 % larger than the diameter of latewood tracheids. In general, it can be concluded that the thickness of latewood tracheids was 1,5 times greater than the thickness of earlywood tracheids. These relationships could be found in sapwood and also in heartwood.

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