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VARIABILITY OF SELECTED MACROSTRUCTURE FEATURES, DENSITY AND COMPRESSION STRENGTH ALONG THE GRAIN OF "TABÓRZ" SCOTS PINE WOOD (*PINUS SYLVESTRIS* L.)

The aim of the study was to determine the variability of annual ring width, share of latewood, density and compression strength along the grain of "Tabórz" Scots pine wood (Pinus sylvestris L.). The wood samples for examination were obtained from three trunks of 260-year-old Scots pines felled in the Sosny Taborskie Nature Reserve. In total, 106 samples were obtained, with cross-sectional dimensions of 20 × 20 mm and a length of 30 mm along the grain. The mean values for all tested wood samples were as follows: annual ring width 1.28 mm, share of latewood 28.9%, wood density 0.487 g·cm^{-3}, and compression strength 47.3 MPa. The least variability within trees was found for wood density and compressive strength along the grain. Very high positive correlation was found between wood density and compressive strength, and high positive correlations were found between share of latewood and wood density and between share of latewood and compressive strength. To the authors' knowledge, the results presented here are the first empirical data published concerning the features of wood macrostructure, density and compression strength along the grain of the Tabórz Scots pine, the trunks of which are considered a valuable timber in Europe.

Keywords: pine, annual ring width, share of latewood, physical and mechanical properties

Introduction

High-quality timber obtained from "Tabórz" Scots pines has been known in Poland and across Europe since approximately the 16th century. The trunks of these pines are full-bodied and knotless within their butt-end parts [Dziekoński 1994, 2004]. Despite the fact that this timber is well-known and highly valued in Poland and Europe, to the authors' knowledge there are no empirical data available in the existing literature that describe this valuable resource in detail.

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In 2014 the research team of the Department of Forest and Wood Utilisation, University of Agriculture in Krakow, began studies on the wood of Tabórz Scots pines, the first part of which addressed the variability in its bending strength [Wąsik et al. 2016]. The aim of the present research was to determine the average values and variability of macrostructural features of Tabórz Scots pine wood, such as annual ring width and share of latewood, as well as the wood density and compression strength along the grain.

Materials and methods

The research material consisted of wood obtained from three pine trees removed in the course of sanitation cutting treatments performed in compartment 94a in the Tabórz subdistrict of Miłomłyn Forest District. Logs of 50 cm length were cut from the felled trees. The samples were taken halfway along the length of each trunk. From each log, a radial board containing the trunk pith was cut along the previously established N-S direction, followed by another radial board cut along the E-W direction. From these boards, longitudinal beams were cut. The beams had square-shaped cross-sections with dimensions of 20 × 20 mm, and a length of 300 mm. The beams were numbered with digits referring to sections of the trunk radius in ascending order: the outermost beams (closest to the bark layer) were given the number 1 (section 1), and the highest number was given to the innermost beams (closest to the trunk pith). Detailed information, including a description and mensuration data of the stand, as well as the methodology employed for sampling the beams, appears in a previous article presenting the results of analyses of variability in the bending strength of Tabórz Scots pine wood, as cited above [Wąsik et al. 2016]. Upon completion of the test of resilience of the investigated wood against static bending, from both ends of the broken beams samples of thickness 30 mm were cut perpendicular to the grain. To improve the visibility of the annual rings, one of the cross-sections of every sample was polished using sandpaper. The cross-sections prepared in this manner were scanned at a resolution of 1200 dpi, to obtain digital images in the form of bitmaps. Then the widths of annual rings (ARW) and widths of latewood zones were measured on these digital images using CooRecorder 7.6 software [Cybis Elektronik & Data AB 2012a]. The measurements included all completely preserved annual rings identified on the cross-section of the sample. Empirical data referring to the annual ring widths and the latewood zone widths were obtained by exporting the results of measurements from CooRecorder 7.6 to the program CDendro 7.6 [Cybis Elektronik & Data AB 2012b]. On this basis, the share of the latewood zone (SLW) was computed for each annual ring. Next, each sample was dried to an absolutely dry state in a Wamed heating chamber (model KBC-65G) at a temperature of 103 ±2°C. The weight of absolutely dry wood was measured to an accuracy of 0.001g with the use of a Radwag laboratory balance (model WPS 210/C). Linear dimensions of the samples were measured in three anatomical directions, using a calliper with an accuracy of 0.05 mm. The wood density (WD) was then calculated as the quotient of the weight of the sample and its volume [PN-77/D-04101].

The compression strength along the grain (CS) of the investigated wood was tested using the EDZ-20 universal machine, within a measurement range of 0-200 kN. Immediately before the test of compression strength, the cross-sectional dimensions of each sample were measured with the use of a calliper to an accuracy of 0.05 mm. The compression strength along the grain was computed for wood with 12% absolute moisture content, using the following formula [PN-79/D-04102]:

$$CS_{12\%} = CS_{w\%}\,[1+\alpha(W-12)]$$

where $CS_{12\%}$ is the compression strength at an absolute moisture content of 12%, $CS_{w\%}$ is the compression strength at the current absolute moisture content, α is the coefficient of change in the wood compression strength along the grain when its moisture content changes by 1%, and W is the current wood moisture content, measured immediately following the test.

Based on the data obtained for two samples taken from the same beam, an arithmetical mean value was computed, which was used in further comparisons and calculations. The data generated included values of ARW, SLW, WD and CS. These data were transferred to a spreadsheet, where mean values and variability coefficients were computed for single sections, individual trees, and the entire material under study. Mean values of WD and CS for a tree were calculated as weighted means, taking account of the a total number of samples within particular sections of the trunk cross-section.

The consistency of empirical distributions with the normal distribution was assessed using the Shapiro-Wilk test. For testing the significance of differences when the assumptions of the parametric test were not satisfied, the Kruskal-Wallis test (K-W test) was employed, followed by the multiple comparison test (mc test). Relationships between the properties under analysis were determined based on Pearson's linear correlation coefficient. In testing of all statistical hypotheses, a significance level of $p \leq 0.05$ was assumed [Stanisz 1998; Statsoft, Inc. 2011].

Results and discussion

The studies covered in total 106 samples cut from logs obtained from trunks of the felled trees. The trees' diameters at breast height and total heights were respectively 50 cm and 28 m (tree no. 1), 51 cm and 30 m (tree no. 2) and 53 cm and 30 m (tree no. 3). The diameters outside bark of 50 cm logs cut from the tree trunks were 37 cm for tree no. 1 and 38 cm for trees nos. 2 and 3.

As noted above in the methods section, the analysed samples were cut from the trunks within particular sections according to geographical directions. Tree no. 1 supplied 42 samples, including eight from each of the first five sections (1-5) and two samples from section 6 (the innermost section). From tree no. 2 a total of 30 samples were obtained, including six from each of the first four sections (1-4), four samples from section 5, and two from section 6. The smaller number of samples taken from tree no. 2 resulted from the presence of a knot within the log on its eastern side, which hindered the cutting of boards from that fragment of the trunk. Tree no. 3 provided 34 samples, including eight from each of the first three sections (1-3), four samples each from sections 4 and 5, and two from section 6.

Annual ring width and share of latewood

The mean ARW computed for the three trees under study amounted to 1.28 mm, while the mean SLW was 28.9%. The mean values of these properties of wood macrostructure determined for particular trees were as follows: 0.99 mm and 39.7% for tree no. 1, 1.57 mm and 22.7% for tree no. 2, and 1.29 mm and 24.4% for tree no. 3. The coefficient of variation calculated for the ARW parameter within individual trees ranged between 35.5% and 67.2%. Significantly lower coefficients of variation were recorded for SLW, ranging from 5.3% to 18.0%. The data presented in Figure 1 indicate that the ARW of the investigated trees decreased from the trunk pith towards the peripheral zone of the trunk (from section 6 to section 1). In trees nos. 1 and 3 the decrease in the ARW value was gradual; the mean ARW values in section 6 (close to the trunk pith) were around 2 mm. In tree no. 2, however, the decrease in ARW values between sections 6 and 4 was more rapid, with a mean annual ring width exceeding 3 mm in the innermost section 6. For each studied tree, the mean ARW values in the three outermost sections (1, 2 and 3) were smaller than 1 mm. The variability in the SLW parameter along the radius of the trunk cross-section within its three innermost sections (4-6) differed between the analysed trees, but in the peripheral zones of the trunks (sections 1-3) the variability in the SLW values was similar, with a small decrease towards the bark layer. No significant differences in annual ring widths were detected between the investigated trees (K-W test: $p = 0.6958$). However, with regard to the SLW parameter it was found that the share of the latewood zone in tree no. 1 was significantly greater than in tree no. 2 (mc test: $p = 0.00000$) and tree no. 3 (mc test: $p = 0.00000$). No significant differences in the SLW value were established between trees nos. 2 and 3 (mc test: $p = 1.00000$)

Wood density

The mean WD of the pine trees under study was 0.487 $g \cdot cm^{-3}$, and its variability between the individual trees amounted to 23.5% (Table 1). Means and coefficients of variation for the investigated trees were as follows: 0.618 $g \cdot cm^{-3}$

Table 1. Mean values of studied wood properties

Tree number	Section	Type of statistic	ARW [mm]	SLW [%]	WD [g·cm^{-3}]	CS [MPa]
1	1	**mean**	**0.59**	**37.3**	**0.600**	**60.1**
		V [%]	12.2	2.4	6.7	3.2
	2	**mean**	**0.72**	**40.8**	**0.657**	**67.4**
		V [%]	12.5	5.0	6.5	5.7
	3	**mean**	**0.95**	**42.7**	**0.650**	**64.9**
		V [%]	14.7	13.8	4.8	9.4
	4	**mean**	**1.29**	**39.2**	**0.606**	**61.2**
		V [%]	19.3	9.1	7.7	16.7
	5	**mean**	**1.39**	**38.5**	**0.584**	**57.3**
		V [%]	5.9	14.4	9.1	12.9
	6	**mean**	**1.93**	**41.8**	**0.591**	**57.6**
		V [%]1))	–	–	–	–
		mean	**1.15**	**40.1**	**0.618**	**61.9**
		V [%]	35.5	5.3	4.7	5.8
2	1	**mean**	**0.75**	**24.0**	**0.432**	**41.0**
		V [%]	22.1	8.7	5.4	11.2
	2	**mean**	**0.91**	**24.7**	**0.443**	**40.6**
		V [%]	22.7	9.6	0.2	6.9
	3	**mean**	**0.83**	**26.4**	**0.440**	**44.3**
		V [%]	2.7	4.2	3.7	5.3
	4	**mean**	**1.19**	**24.4**	**0.451**	**40.7**
		V [%]	23.0	8.5	0.7	11.1
	5	**mean**	**2.47**	**21.7**	**0.409**	**37.9**
		V [%]	14.6	12.9	3.8	5.2
	6	**mean**	**3.29**	**14.9**	**0.398**	**39.3**
		V [%]1)	–	–	–	–
		mean	**1.57**	**22.7**	**0.434**	**41.0**
		V [%]	67.2	18.0	3.6	4.7
3	1	**mean**	**0.76**	**21.4**	**0.387**	**36.2**
		V [%]	11.3	13.3	3.7	8.5
	2	**mean**	**0.87**	**22.1**	**0.397**	**38.3**
		V [%]	18.9	7.2	4.1	5.3
	3	**mean**	**0.90**	**22.8**	**0.408**	**40.1**
		V [%]	15.0	13.0	5.7	8.3

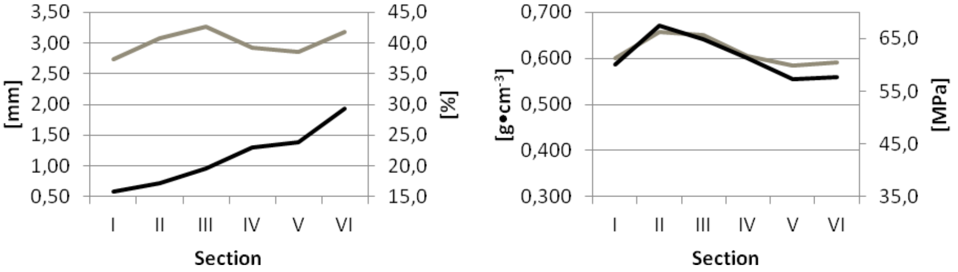
4		**mean**	**1.09**	**25.6**	**0.433**	**40.0**
		V [%]	10.0	7.2	1.4	4.2
5		**mean**	**1.87**	**25.2**	**0.428**	**40.1**
		V [%]	14.6	2.2	3.6	2.7
6		**mean**	**2.22**	**29.5**	**0.439**	**43.4**
		V [%][1)]	–	–	–	–
	mean		**1.29**	**24.4**	**0.408**	**38.9**
	V [%]		47.4	12.2	4.3	4.8
mean			**1.33**	**29.1**	**0.487**	**47.3**
V [%]			16.3	33.2	23.5	26.9

V – coefficient of variation; [1)] – data obtained from the analysis performed for one of the samples

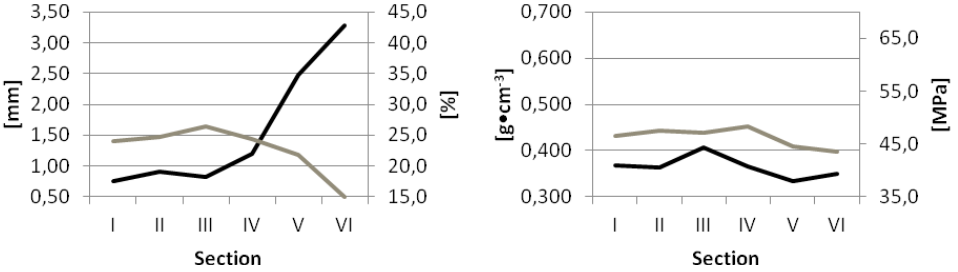
and 4.7% for tree no. 1, 0.434 g·cm^{-3} and 3.6% for tree no. 2, and 0.408 g·cm^{-3} and 4.3% for tree no. 3. The data presented in Figure 1 indicate that in trees nos. 2 and 3, the WD decreased slightly from section 4 towards the trunk perimeter (section 1). In the case of tree no. 1, however, there was a visible increase in this parameter from section 5 to 2, followed by a decrease in section 1. Also notable are the clearly higher values of wood density in particular sections of tree no. 1 compared with those of the other two trees. The analyses confirmed that the WD parameter took significantly higher values for tree no. 1 than for tree no. 2 (mc test: p = 0.00000) and tree no. 3 (mc test: p = 0.00000), while the WD of tree no. 2 was significantly higher than that of tree no. 3 (mc test: p = 0.03976).

Compression strength along the grain

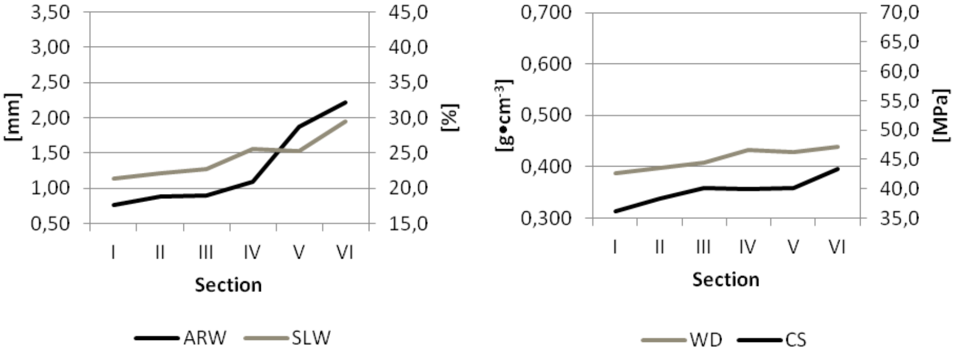
The mean CS value of the trees under study was 47.3 MPa, with the following mean values for individual trees: 61.9 MPa for tree no. 1, 39.3 MPa for tree no. 2, and 43.4 MPa for tree no. 3 (Table 1). The coefficient of variation between the investigated trees amounted to 26.9%, with values for individual trees ranging from 4.7% to 5.8%. Based on the data presented in Figure 1, it may be stated that the variability in the CS value within sections along the trunk cross-section radius exhibited slightly different tendencies for each of the analysed pine trees. In tree no. 1 the CS increased from the trunk pith towards section 2, and significantly decreased within the outermost section 1. The wood of tree no. 2 revealed a considerable increase in the CS value between sections 5 and 3, followed by a decrease between sections 3 and 1. In tree no. 3, however, there was a gradual decrease in the CS parameter from the pith towards the trunk perimeter. In all of these cases, the curve representing the variability in CS had a shape similar to that of the curves representing the variability in WD. Statistical analyses proved that the CS of tree no. 1 was significantly higher than that of tree no. 2 (mc test: p = 0.00000) and tree no. 3 (mc test: p = 0.00000). No significant differences in the CS parameter were established between trees nos. 2 and 3 (mc test: p = 1.00000).



TREE no. 1



TREE no. 2



TREE no. 3

Fig. 1. Variability of the studied wood properties within particular sections of the trunk cross-sections

Correlations between the studied features

The data presented in Table 2 indicate that there was no significant correlation between the parameters ARW and SLW, while with respect to other properties they were significantly correlated within the assumed level of statistical significance. Negative and neutral correlations were detected between values of ARW and those of WD and CS, while strong positive correlations occurred between values of SLW and those of WD and CS. Finally, the correlation between WD and CS was positive and extremely strong.

Table 2. Coefficients of correlation between the studied wood properties

Property	ARW	SLW	WD
SLW	-0.01104	–	
WD	-0.35871*	0.63974**	–
CS	-0.37228*	0.68130**	0.79410**

* – significant for p = 0.05, ** – significant for p = 0.001.

The mean ARW value obtained in these studies was 1.28 mm, which means that the wood of the studied trees can be classified as fine-ringed timber (less than 3.0 mm) [Krzysik 1974]. Similar mean values were recorded for pine trees growing in coniferous stands in the eastern part of Poland [Paschalis 1980] and for pines from stands in the Carpathian and Sudety Mountains in southern Poland [Niedzielska et al. 2001]. Slightly higher means, though not exceeding the value of 2.00 mm on average, were reported for trunks of pine trees in Lithuania [Aleinikovas and Grigaliūnas 2006], while markedly higher values in the range 2.86-3.72 mm were obtained for Scots pines in Portugal [Fernandes et al. 2017]. Noteworthy are the surprisingly narrow annual rings within the peripheral zones of the trunks, the mean values of which ranged from 0.95 mm to 0.59 mm. The narrowest annual ring measured in the present study had a width of 0.13 mm, and occurred in section 3 of tree no. 1, while the widest was found in section 5 of tree no. 2, with a width of 4.22 mm.

The mean SLW recorded for the pine trees under study was 28.9%, and this parameter exhibited significantly less variability within all of the investigated trees than ARW. The variability in the former parameter between the particular trees was relatively high, resulting from the significantly higher mean SLW found in the trunk of tree no. 1 (40.2%) than in trees nos. 2 and 3 (22.7% and 24.4% respectively). Similar values of SLW were recorded for pine trees growing in eastern Poland (21.0-36.2%) [Paschalis 1980], while slightly higher values were found in trees from mountain regions in southern Poland (27.9-54.7%) [Niedzielska et al. 2001], in Lithuania (33.5-39.7%) [Aleinikovas and Grigaliūnas 2006] and in Portugal (33.3-40.4%) [Fernandes et al. 2017]. The variability in the SLW parameter within the particular trunk sections was different for each of the trees under study. Noteworthy is the rapid increase in the SLW value found in the trunk of tree no. 2 in its innermost zones, close to the pith, which was accompanied by an equally rapid decrease in the ARW value.

The coefficient of variation between the investigated trees computed for the WD parameter was 23.5%. Considerably smaller variability in this property was recorded within the particular trees, for which the coefficients of variation ranged between 3.6% and 4.7%. The mean WD value was 0.487 $g{\cdot}cm^{-3}$, which means that the studied Tabórz Scots pine trees can be placed in the group of trees with light wood, with density between 0.4 and 0.5 $g{\cdot}cm^{-3}$ [Krzysik 1974]. Assuming that the total volumetric shrinkage remains at a level of 12% [Krzysik 1974], the WD values obtained for pine trees both from eastern Poland (from 0.552 $g{\cdot}cm^{-3}$ to 0.715 $g{\cdot}cm^{-3}$) [Paschalis 1980] and from southern Poland (0.518 $g{\cdot}cm^{-3}$) [Niedzielska et al. 2001] must be considered higher. Higher densities of Scots pine wood were also recorded in Lithuania (0.572--0.586 $g{\cdot}cm^{-3}$) [Aleinikovas and Grigaliūnas 2006], in Portugal (0.497--0.621 $g{\cdot}cm^{-3}$) [Fernandes et al. 2017] and in Spain (0.556 $g{\cdot}cm^{-3}$) [Riesco--Muñoz et al. 2008]. A similar density was found in Scotland (0.483 $g{\cdot}cm^{-3}$) [Auty et al. 2014], and a slightly lower value in Sweden (0.454 $g{\cdot}cm^{-3}$) [Wilhelmsson et al. 2002].

The results of studies by Repola [2006] and Witkowska and Lachowicz [2012, 2013] indicate that the WD of pine trees decreased from the butt end towards the tip of the trunk. On this basis, the authors make the assumption that the wood from the butt-end parts of trunks of Tabórz Scots pines would exhibit a greater density than that from the mid-height parts of the trunks.

The mean CS value of the wood under examination was 43.7 MPa, with values for particular trees ranging from 38.8 MPa to 61.9 MPa. These values lie within the relatively wide range of resilience against compression force determined for pine wood by Krzysik [1974] and Galewski and Korzeniowski [1958], with values from ca. 30 MPa to ca. 78 MPa, and a mean of 46 MPa. A higher mean CS value (76.11 MPa) was obtained for the wood of pine trees from Lithuania, where the minimum value was 37.4 MPa and the maximum 113.4 MPa [Aleinikovas and Grigaliūnas 2006]. In the present study the lowest CS value of 29.2 MPa was recorded for a sample obtained from section 4 of tree no. 2, while the highest value, as high as 77.3 MPa, was determined for a sample from section 3 of tree no. 1. Taking into account that the research material was sampled from the tree trunks at mid-height, the authors make the assumption that the CS of the Tabórz Scots pines under analysis would take higher values in the butt-end parts of their trunks. The possibility of such a pattern is supported by the results of studies on the wood of pine trees growing in north-eastern and southern Estonia, where the CS recorded at the mid-height of their trunks was nearly 30% lower than that measured at one-fourth of the tree height [Pikk and Kask 2004]. If it is assumed that the investigated Tabórz Scots pine wood exhibits similar proportions, the estimated mean CS value within the butt-end part of their trunks would be ca. 56 MPa, which is only slightly higher than the mean CS values reported for pine wood by Krzysik [1974] and by Galewski and Korzeniowski [1958].

The correlation between the ARW and SLW values determined in this study was very weak and proved to be insignificant. This contrasts with the pattern commonly reported for the wood of coniferous tree species, whereby as the ARW decreases, the SLW value increases. Perhaps, in the case of wood containing extremely narrow annual rings, such a pattern simply does not occur. Nevertheless, the correlations established in this study between the values of WD and those of ARW and SLW confirm the existence of dependences between these properties that have also been recorded in studies of the wood of other coniferous species [Niedzielska 1995; Wąsik 2007; Wąsik et al. 2015]. The strong correlation between the WD and CS parameters indicates that pine wood with higher density was characterised by higher CS values. Similar conclusions can be drawn from investigations of the wood of pine trees growing in north-eastern and southern Estonia [Pikk and Kask 2004].

The mean values of the parameters analysed in these studies for Tabórz Scots pine wood were not very different from those reported for pine wood obtained from other regions of Poland. The great popularity of Tabórz Scots pines in Poland and across Europe would appear to be due to the extremely high quality of their full-bodied and knotless trunks, rather than physicochemical properties of their wood [Dziekoński 1994, 2004].

Conclusions

1. The mean value of annual ring widths (ARW) was 1.28 mm, which supports the classification of the studied Tabórz Scots pine wood as fine-ringed wood. In the three outermost sections of the trunks the mean widths of annual rings did not exceed 1 mm.
2. The mean share of latewood (SLW) was 28.9%. Similar values have been reported for the wood of pine trees growing in eastern Poland, while values reported for trees from southern Poland are slightly higher.
3. The mean value of wood density (WD) was 0.487 $g \cdot cm^{-3}$, which means that Tabórz Scots pine can be categorised in the group of species with light wood. Amongst the wood properties analysed, wood density revealed the smallest variability within the studied individual trees.
4. The mean value of compression strength along the grain (CS) of the wood under analysis was 43.7 MPa. Given that the investigated wood samples were taken at the mid-height of the trunks, and assuming that the compression strength of wood at a height of 0.5 m is ca. 30% higher [Pikk and Kask 2004], the estimated compression strength of the wood in the butt-end part of the trunks of Tabórz Scots pines can be expected to be ca. 56 MPa, which slightly exceeds the corresponding mean values cited in the existing Polish literature.
5. The annual ring width exhibited high variability within the examined trees, and clearly smaller variability between them. The share of late wood, the density and the compressive strength along the grain exhibited greater variation between trees than within individual trees.

6. A slight negative correlation between ARW and WD was recorded, while between the values of SLW and those of WD and CS a strong positive correlation was observed. An extremely strong correlation was established between WD and CS. These relationships confirm the results of previous studies on coniferous species which indicate mutual dependence between these properties of wood macrostructure, namely its density and mechanical properties.

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List of standards

PN-79/D-04102:1980 Drewno – Oznaczanie wytrzymałości na ściskanie wzdłuż włókien. (Wood – Determination of ultimate stress in compression parallel to grain)

PN-77/D-04101:1978 Drewno – Oznaczanie gęstości. (Wood – Determination of density)

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