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ON SOME ASPECTS OF A RELATION BETWEEN DENSITY AND MECHANICAL PROPERTIES OF WOOD IN LONGITUDINAL DIRECTION

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Abstract. A comprehensive analysis has been made of the mechanical properties and density of 100 timber species. The correlation between the mechanical properties and wood density has been approximated by a power function type $y = a\rho^n$. No functional relation has been found between the parameters describing mechanical properties of the cell wall and the wood density. The values of these parameters show great scatter of about ±50% relative to the mean value. An attempt has been made to identify other wood characteristics determining the mechanical properties of wood. The species characterised by extremely high values of the parameters describing mechanical properties of wood have been singled out. The greatest differentiation in the values has been noted for the tensile strength. Among the coniferous species of similar density the differences have reached 113% on average, while among the deciduous species – 143%, at the differences in density being only of 15%.

Key words: softwood, hardwood, cell wall, wood density, strength

INTRODUCTION

Wood is characterised by a significant heterogeneity, not only interspecies but intraspecies or even within single trees [Kučera 1994, Zobel and Buijtenen 1989]. For almost 100 years, attempts have been made to describe mathematically relations between the mechanical properties of wood and its density [Newlin and Wilson 1919]. The character of this relation has been one of the most important till today. It has been generally assumed that density is the most important feature of wood and determines its strength, it has been used to characterise the mechanical properties of wood and to indicate its quality as well as to predict its end-use properties [Panshin and Zeeuw 1970, Dinwoodie 1981]. It is known that with increasing density the values of parameters describing its mechanical properties increase and are generally highly correlated with

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wood density [Niemz 1993, Zhang 1994]. Moreover, with increasing density the anisotropy of the physical and mechanical properties of wood decreases [Kollmann 1982].

Wood characterised by high anisotropy and inhomogeneity is much more difficult to describe in mathematical terms than metals and plastics. For many decades a relation between the wood mechanical properties and density has been described by linear equations as within particular species the linear regression has been assumed to best describe it [Forest... 1987, Pearson and Gilmore 1971, Schniewind and Gammon 1983, Shepard and Shottafer 1992]. However, on the basis of a comprehensive study of a few hundred timber species from different geographical regions [Newlin and Wilson 1919, Markwardt 1930, Armstrong et al. 1984, Zhang 1994, 1997] it has been established that the relation between wood density and its strength is better approximated by curvilinear dependencies. Nevertheless, because of great dispersion of wood properties, although they are strongly correlated with density, the empirical equations proposed hitherto permit only a rough estimation [Kollmann 1982, Armstrong et al. 1984]. According to Zhang [1994], despite relatively high coefficients of determination (R^2 = 0.7-0.8) of the correlation analysed, the scatter of results is significant. For instance for hardwoods of similar density, the values of the modulus of elasticity (MOE) and modulus of rupture in static bending (MOR) can vary in wide ranges from –25 to +85% and from –30 to +110% of the values calculated from the regression equations, respectively.

Recently, since the 1990s, much attention has been paid to the structure of the cell walls, mainly in the aspect of the effect of its ultrastructure on the mechanical properties of the wood tissue and individual grains. Earlier studies concerned mainly the relations between the submicroscopic structure of grains and the properties of the paper obtained [Page et al. 1977] and – in regard to the solid wood – the relations between the cell wall structure and the moisture strain and their anisotropy [Harris and Meylan 1965, Meylan 1972, Yamamoto et al. 2001]. The qualitative character of the relation between the submicroscopic structure of the cell wall and the mechanical wood properties is known. The latter, in particular the tensile strength parallel to the grain, depend on the degree of polymerisation of cellulose and the microfibrils angle (MFA) in the cell wall. High values of the modulus of elasticity (MOE) of cellulose determine the properties of wood along the microfibrils [Thuvander et al. 2002]. Mechanical, rheological and physical properties of solid wood and individual grains are directly related to the orientation of microfibrils [Meylan 1972, Page et al. 1977, Houska and Bucar 1996, Watanabe and Norimoto 1996, Alméras et al. 2005, Entwistle 2005]. The lower the MFA the greater the strength and MOE and the lower the moisture strain of wood along the grains [Suzuki 1969, Yamamoto and Kojima 2002]. The studies of the elasticity of wood grains have shown that small changes in the MFA for the angles smaller than 15°, result in significant changes in the axial modulus of elasticity of grains [Mark and Gillis 1973]. In late wood the orientation of microfibrils is more ordered than in the early wood, so the late wood walls are stronger. The "in situ" study of the mechanical properties of the cell walls has shown that the hardness and the MOE of the walls of late wood tracheids are higher than those of the early wood [Wimmer et al. 1997]. The mechanical properties of the cell wall are mainly determined by the S2 layer of the secondary cell wall as its contribution in the cell wall is dominant (80-90%) and it is characterised by ordered microfibrils [Houska and Bucar 1996, Wagenführ 1999, Anagnost et al. 2002]. The MFA values have been found a good criterion of the width of juvenile wood [Wimmer 1992, Yang 1994, Passialis and Kiriazakos 2004].

In the context of the relations between the cell wall structure and the properties of grains and wood tissue, the question arises if the wood density is really the most important and sufficiently informative parameter describing the mechanical properties of wood and its quality. The aim of the study is to analyse the available data on the mechanical properties and density of wood in order to answer the above question.

MATERIAL AND METHODS

The analysis presented in this paper has been performed on the basis of the literature data. The values of the parameters describing wood mechanical properties and density and the sizes of anatomical elements of particular species have been taken from the following sources:

1. Kollmann F., Technologie des Holzes und der Holzwerkstoffe. Springer Berlin 1982.
2. Sell J., Eigenschaften und Kenngrößen von Holzarten. Baufachverlag AG Zűrich 1989.
3. Wagenfűhr R., Holzatlas. Fachbuchverlag Leipzig 2000.

The subjects of analysis were the numerical data describing the mechanical properties and density of 100 timber species belonging to 41 families coming from different geographical regions, characterised by high variation in density and representing different wood categories (softwood, hardwood: ring- and diffuse-porous wood category). The parameters describing the mechanical properties considered were the mean values of air dry wood density, maximum crushing strength, maximum tensile strength and modulus of elasticity along the grains, and a modulus of rupture in static bending in the air dry state. The analysis was made only for those species for which at least three of the four parameters describing mechanical properties were published in literature. When literature sources gave different values of the same parameters all values were taken into regard, when all literature sources gave the same values – the value was included only once.

Relations between the parameters describing the mechanical properties and the wood density were approximated by power functions and the results were compared with those of other functions proposed in literature.

As the relation between the contribution of the cell walls and the contribution of pores changes significantly among the timber species, in this study the subject of concern was a relation between the mechanical parameters and density only, disregarding the effect of porosity. Thus, a correlation was made between the strength and modulus of elasticity of cell walls and the wood density. The parameter describing the mechanical properties of the cell wall was calculated as the product of the same parameter describing the mechanical properties of wood and the quotient of the density of wood substance to that of air dry wood. The density of the wood substance assumed in the calculations was 1.5 $g \cdot cm^{-3}$ [Wilfang 1966, Niemz 1993].

RESULTS AND DISCUSSION

Relations between the parameters describing mechanical properties of the timber species analysed and their density are presented in Figure 1. The relations between the maximum crushing strength (MCS), maximum tensile strength (MTS), modulus of rupture (MOR), modulus of elasticity (MOE) and the wood density (ρ) were approximated by power functions of the type $y = a\rho^n$ successfully used for this purpose. In general, the character of the relations obtained is consistent with the results of the earlier study by Armstrong et al. [1984] and Zhang [1994], performed on about 1500 commercially important timbers representing different world regions and 342 species

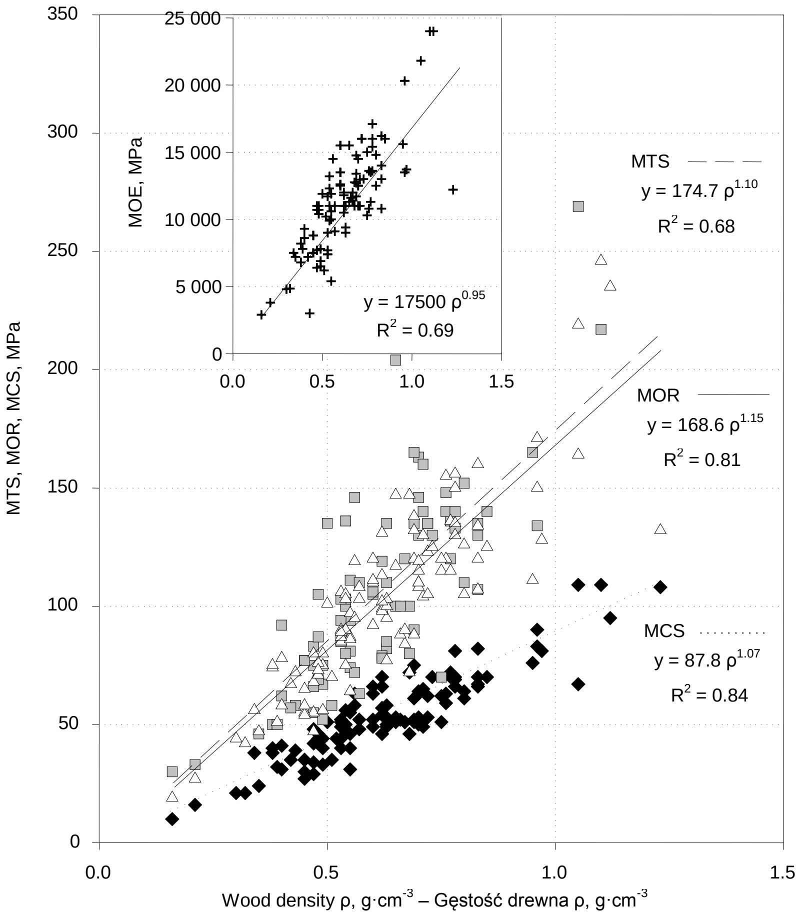

Fig. 1. Maximum crushing strength of wood in compression parallel to the grain (MCS), maximum tensile strength parallel to the grain (MTS), modulus of rupture in static bending (MOR) and modulus of elasticity in static bending (MOE) versus the wood density (ρ)

Rys. 1. Zależność wytrzymałości drewna na ściskanie (MCS) i rozciąganie (MTS) wzdłuż włókien, na zginanie (MOR) oraz modułu sprężystości liniowej (MOE) od gęstości drewna (ρ) growing in China. Analysis of these relations for softwood and hardwood together has shown that the lowest value of ***n***, slightly smaller than one, described the relation between the MOE and wood density, while the highest value of ***n***, greater or equal one, described the relation between the MCS and MOR and wood density. The values of the constant ***a*** obtained were almost the same as reported by other authors. The determination coefficients (R^2) of the relations were high, ranging from 0.7 to 0.9 (Table 1).

Table 1. The constans in the regression equations $y = a\rho^n$ relating mechanical properties to wood density
Tabela 1. Stałe w równaniach regresji $y = a\rho^n$ opisujących właściwości mechaniczne drewna w funkcji gęstości

Wood property Właściwości drewna	Wood category Rodzaj drewna	Constans Stała		R^2	Source of data Źródło
		a	n		
MCS	S	68.3	0.83	0.53	Zhang 1994
	H	68.8	0.93	0.78	
	S + H	85.3	0.95	0.88	Armstrong et al. 1984 Armstrong i in. 1984
	S	76.5	0.78	0.66	author autor
	H	88.5	1.12	0.86	
	S + H	87.8	1.07	0.84	
MTS	S	161.0	0.76	0.36	Zhang 1994
	H	158.0	0.82	0.60	
	S	186.8	1.02	0.31	author autor
	H	175.0	1.15	0.72	
	S + H	174.7	1.10	0.68	
MOR	S	149.6	0.95	0.61	Zhang 1994
	H	145.0	1.00	0.81	
	S + H	167.4	1.03	0.89	Armstrong et al. 1984 Armstrong i in. 1984
	S	144.7	0.89	0.56	author autor
	H	169.6	1.13	0.81	
	S + H	168.6	1.15	0.81	
MOE	S	14 900	0.59	0.21	Zhang 1994
	H	16 200	0.80	0.73	
	S + H	19 400	0.85	0.79	Armstrong et al. 1984 Armstrong i in. 1984
	S	18 400	0.81	0.67	author autor
	H	17 600	1.03	0.73	
	S + H	17 500	0.95	0.69	

MCS – maximum crushing strength in compression parallel to the grain, MTS – maximum tensile strength parallel to the grain, MOR – modulus of rupture in static bending, MOE – modulus of elasticity in static bending, S – softwood, H – hardwood, R^2 – coefficient of determination.
MCS – wytrzymałość na ściskanie podłużne, MTS – wytrzymałość na rozciąganie podłużne, MOR – wytrzymałość na zginanie, MOE – moduł sprężystości, S – drewno iglaste, H – drewno liściaste, R^2 – współczynnik determinacji.

Analysis of the data given in Table 1 on the regression equations found for particular wood categories and particular parameters, has revealed that the constants ***a***, ***n*** and the determination coefficients are almost the same as the literature values for MOR, close for MCS and slightly higher for MTS and MOE. The same data imply that the wood density shows the greatest correlation with MCS and the weakest with MTS, which is consistent with the observations by other authors [Zhang 1994].

The correlations between the parameters describing the mechanical properties of cell walls with the wood density of the species analysed are illustrated in Figure 2. They were could not be approximated by functional dependencies. The determination coefficients of linear regression (R^2) assumed values from 0.0002 to 0.03, which means that

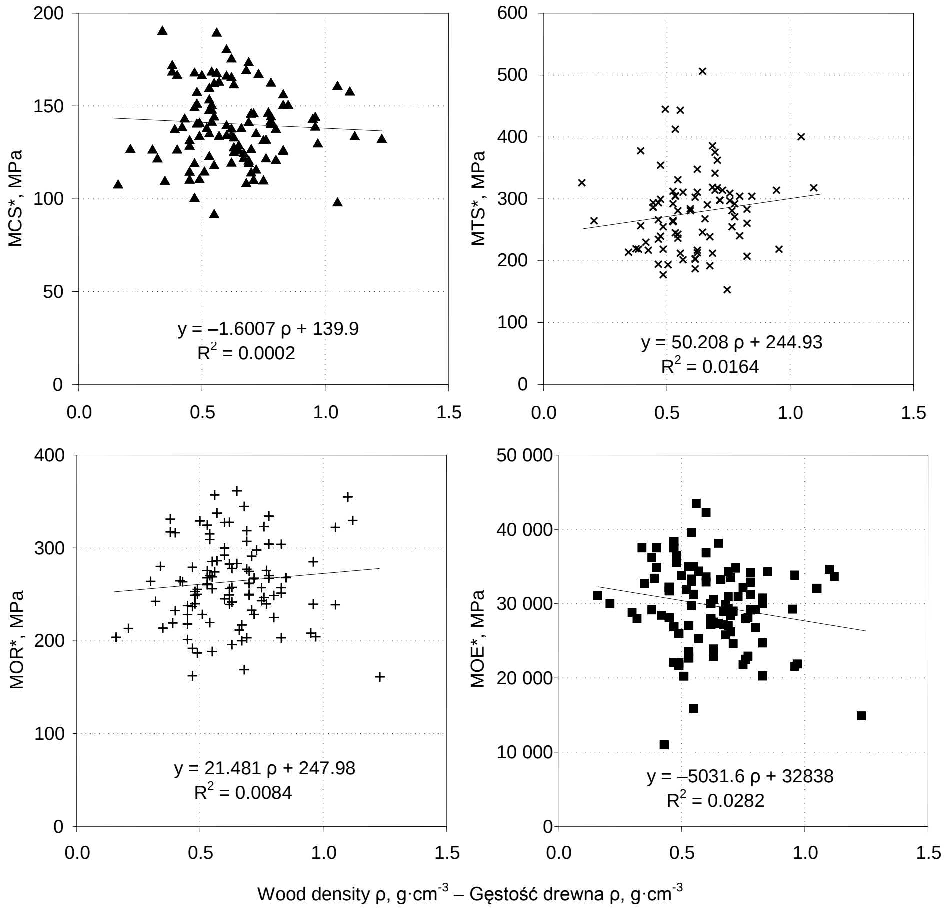

Fig. 2. Maximum crushing strength of cell wall in compression parallel to the grain (MCS*), maximum tensile strength parallel to the grain (MTS*), modulus of rupture in static bending (MOR*) and modulus of elasticity in static bending (MOE*) versus the wood density (ρ)

Rys. 2. Zależność wytrzymałości ścian komórkowych na ściskanie (MSC*) i rozciąganie (MTS*) wzdłuż włókien, na zginanie (MOR*) oraz modułu sprężystości linowej (MOE*) od gęstości drewna (ρ) the mechanical properties of the cell walls practically do not depend on the wood density. If not for the differences in the ultrastructure of the cell walls, it could be expected that the parameters describing the mechanical properties would be constants independent of the timber species. However, the values of these parameters revealed great scatter of ±50% relative to the mean value. The parameters MCS, MTS, MOR and MOE of the cell walls took values from the ranges: 90-190, 150-500, 170-370 and 11 000-44 000 MPa. These differences mean that the strength and MOE of the cell walls depend significantly on their ultrastructure, so it can be concluded that the mechanical properties of wood tissue are determined by the submicroscopic structure of the cell walls.

This supposition is supported by the results of e.g. Krauss [2005] who studied the swelling pressure of spruce wood and proved that the tensile strength and swelling pressure along the grains of the compression wood take much lower values than those of the normal wood, despite a higher density of the compression wood. The author indicated the structure of the cell walls of the tracheids as a possible reason for the differences observed.

For preliminary verification of the thesis that the wood density is not sufficient to characterise the mechanical properties of wood, an analysis of the relation between them was made for the species characterised by the extreme values of the parameters describing mechanical properties of the cell walls. Three species characterised by at least three of the four analysed mechanical parameters taking maximum values (Group A) or minimum values (Group B), representing each category of wood were selected. Table 2 presents the mean values of the wood density, fibre or tracheids length, MCS, MTS, MOR and MOE of the species from groups A and B and some other ones. The values of MCS, MTS and MOR are given to the accuracy of 1 MPa, the values of MOE – to the accuracy of 100 MPa, the length of fibres and tracheids to 0.1 mm, and the wood density to 0.01 $g \cdot cm^{-3}$.

Analysis of the data given in Table 2 permits the following observations. For the softwood the representatives of groups A and B have practically the same mean density and mean length of the axial anatomical elements, while their mechanical properties differ significantly. The wood of group A species shows much higher values of MCS, MTS, MOR and MOE, higher from those of the wood of group B species by 23, 113, 41 and 22%, respectively. The data indicate that the wood density cannot account for the increase in these parameters of mechanical properties. The analysis of the Table 2 data suggests that there are other factors determining the mechanical properties of wood, independent of the wood density and probably related to the ultrastructure of cell walls.

For the hardwood, the representatives of group A have on average by 15 and 12% higher wood density and greater fibre length and by 71, 143, 111 and 100% higher values of MCS, MTS, MOR and MOE then the group B representatives. Such a great diversity of the mechanical properties, in particular MTS, can hardly be explained by a relatively small increase in the wood density. A probable reason for the increase in these parameters, can be the ultrastructure of cell walls of the species showing extreme values of the parameters. The differences in the mean fibre length may suggest different microfibril angles in the cell walls of group A and group B species, which may lead to differences in the parameters describing mechanical properties. Taking into regard small differences in the mean fibre length and great diversity of anatomical elements making the wood tissue of hardwood it is difficult to indicate on the basis of the data analysed which anatomical elements and which features of their structure are responsible for such a great diversity of the wood mechanical parameters. However, a synergic effect of the structure of fibres and vessels on the mechanical properties of deciduous species cannot be excluded.

Table 2. Mean values of air dry wood density (ρ), length of tracheids (LT), length of fibers (LF), maximum crushing strength in compression parallel to the grain (MCS), maximum tensile strength parallel to the grain (MTS), modulus of rupture in static bending (MOR) and modulus of elasticity in static bending (MOE) for wood species showing maximum (A) and minimum (B) values of examinated wood properties at air dry conditions, as well as mean values of this properties of whole group A and B for each wood category (softwood and hardwood)

Tabela 2. Wartości średnie gęstości (ρ), długości cewek (LT), długości włókien (LF), wytrzymałości na ściskanie podłużne (MCS), wytrzymałości na rozciąganie podłużne (MTS), wytrzymałości na zginanie (MOR) i modułu sprężystości (MOE) drewna gatunków wykazujących maksymalne (A) i minimalne (B) wartości badanych właściwości oraz średnie wartości tych właściwości dla grupy A i B dla każdej kategorii drewna (drewno iglaste, drewno liściaste)

Wood species – Gatunki drewna		ρ	LT/LF	MCS	MTS	MOR	MOE
botanical name nazwa botaniczna	commercial name nazwa handlowa	$g \cdot cm^{-3}$	mm	MPa			
1	2	3	4	5	6	7	8
Softwood (A) – Drewno iglaste (A)							
Fitzroya cupressoides Johnst.	Alerce ficroja cypryso-wata	0.38	2.4	38	–	75	8 200
Aghatis alba Foxw.	Malayan kauri soplica biała	0.46	6.2	51	135	101	11 900
Araukaria angustifolia O. Ktze	Parana pine araukaria	0.50	7.2	56	136	103	13 200
Average (A) – Średnia (A)		0.45	5.3	48	136	93	11 100
Softwood (B) – Drewno iglaste (B)							
Tuja plicata D. Don	Western redcedar żywotnik olbrzymi	0.35	4.6	32	50	51	7 800
Sequoia sempervirens Endl.	Californian redwood sekwoja	0.45	6.1	35	77	57	7 500
Pinus palustris Mill.	Longleaf pine sosna błotna	0.67	4.9	50	–	90	12 000
Average (B) – Średnia (B)		0.43	5.2	39	64	66	9 100
Softwood A:B – Drewno iglaste A:B		1.05	1.02	1.23	2.13	1.41	1.22
Hardwood (A) – Drewno liściaste (A)							
Gonystylus bancanus Baill.	Ramin ramin	0.56	1.4	66	–	120	15 500
Betula verrucosa Ehrh.	Common birch brzoza	0.61	1.0	51	204	147	15 500
Shorea polysperma Merr.	Dark red meranti meranti	0.67	1.3	63	146	119	14 500
Average (A) – Średnia (A)		0.61	1.23	60	175	129	15 200

Table 2 – cont. / Tabela 2 – cd.

1	2	3	4	5	6	7	8
Hardwood (B) – Drewno liściaste (B)							
Salix alba L.	White willow wierzba	0.44	1.0	29	55	47	6 400
Aesculus hippocastanum L.	Horse chestnut kasztanowiec	0.51	1.1	31	81	64	5 400
Ulmus carpinifolia Gled.	Elm wiąz	0.64	1.2	46	80	72	11 000
Average (B) – Średnia (B)		0.53	1.10	35	71	61	7 600
Hardwood A:B – Drewno liściaste A:B		1.15	1.12	1.71	2.43	2.11	2.00

CONCLUSIONS

Strength of wood along the grains is determined by the strength of its cell walls. The density of the cell walls in different species does not show a great variation and the density of the wood substance can be approximately assumed as a constant, except for the reaction wood. The wood density is a function of packing of the wood substance in a unit volume, so assuming insignificant differences in the cell wall structure, a close to linear character of the dependence of the wood strength parallel to the grains on the wood density is rather obvious. Under this assumption the strength of the cell walls along the grains should be a constant, independent of the timber species. However, the above analysis has shown that this is not the case. Therefore, in the context of the results analysed it seems justified to suppose that the mechanical properties of wood parallel to the grains depend on the structure of the cell wall and the main parameter determining their values is the microfibril angle in the S-2 layer.

Explanation of the unexpectedly great diversity in the mechanical properties of the cell walls and wood of close density, so identification of the factors other than density determining these properties, requires further comprehensive studies. Results of the analyses made in this paper indicate that a significant factor determining the mechanical properties of wood can be the structure of cell walls. This suggestion is supported by the reported close relations between the microfibril angle and the modulus of elasticity of the cell wall and the modulus of elasticity of wood. From the mechanical point of view the modulus of elasticity determines the wood strength. On the microscopic level the mechanical properties of wood can be determined by the length of the anatomical elements, while on the submicroscopic level by the microfibril angle.

In conclusion, it seems that the use of wood density as the main parameter characterising wood properties and its quality needs to be verified. As follows from all the above indications an attempt should be made to relate the mechanical properties of wood with its structure on the submicroscopic level. As this paper presented analysis of the mean values of the parameters describing mechanical properties of wood taken from literature, the author only wishes to indicate the need for further study on the role of the microfibril angle in determination of the macro-properties of wood.

1. Wood density is not a sufficient parameter determining the wood strength in the longitudinal direction.
2. A probable reason for the intra- and inter-species differences in the mechanical properties in the longitudinal direction of wood of the same density is the microfibril angle in cell walls of the axial anatomical elements of the wood tissue.

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O ZWIĄZKACH MIĘDZY GĘSTOŚCIĄ A WŁAŚCIWOŚCIAMI MECHANICZNYMI DREWNA WZDŁUŻ WŁÓKIEN

Streszczenie. Analizowano niektóre właściwości mechaniczne i gęstość 100 gatunków drewna. Podjęto próbę wskazania na inne, poza gęstością, czynniki decydujące o właściwościach mechanicznych drewna. Związki między właściwościami mechanicznymi i gęstością drewna opisano funkcją potęgową typu $y = a\rho^n$. Nie stwierdzono natomiast zależności funkcyjnych między właściwościami mechanicznymi ściany komórkowej i gęstością drewna. Zaobserwowano duży rozrzut wartości właściwości mechanicznych ścian komórkowych wynoszący do około ±50% w stosunku do wartości średniej. Wskazano na gatunki charakteryzujące się ekstremalnymi wartościami właściwości mechanicznych. Największe zróżnicowanie odnotowano w wytrzymałości drewna na rozciąganie podłużne, dla gatunków iglastych wynosiło ono średnio 113%, a dla gatunków liściastych – 143%, przy gęstości różniącej się odpowiednio o 5% i 15%.

Słowa kluczowe: drewno gatunków iglastych, drewno gatunków liściastych, ściana komórkowa, gęstość, wytrzymałość

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