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Impact of annual growth pattern on swelling of selected wood species

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Abstract: *Impact of annual growth pattern on swelling of selected wood species.* Unit swelling was investigated in radial and tangential directions as well as in the intermediate directions for wood of density ranging from 300÷500 kg/m^3 and 500÷700 kg/m^3 and above 700 kg/m^3. Species selected included pine – PNSY (*Pinus sylvestris L.*), oak – QCXE (*Quercus. robur L.*) and bangkirai – SHBL (*Shorea spp*.), teak – TEGR (*Tectona grandis*), merbau – INXX (*Intsia bijuga*), jatoba – HYCB (*Hymenaea courbaril L*). For all the studied wood species, the lowest swelling in the radial direction (0°) was found after both 2 h and 24 h of wetting in water, which increased with the angle of inclination of the annual growth and, after reaching 90°, corresponded to the maximum swelling in the tangential direction. For pine (PNSY) sapwood and heartwood and for oak (QCXE), a high swelling unit was obtained after a wetting time of 2 h, with little change after 24 h of wetting. Swelling increments for the other wood species were lower, ranging from 1% to over 2% after a wetting time of 2 h, showing slight differences between radial and tangential directions. For these wood species, after 24 h of wetting the swelling was higher and varied from more than 2% to nearly 5% in the radial direction and from more than 4% to 10% in the tangential direction. The study showed that, for high-density wood species, it becomes necessary to extend the wetting time in order to determine the actual maximum swelling per unit. The swelling anisotropy coefficients ε of the studied wood species corresponded to the values found in the literature. Higher coefficients were found for oak (QCXE) and teak (TEGR), bangkirai (SHBL) and jatoba (INXX), and were related to the characteristic features of the density structure and anatomical structure. The unit swelling values calculated with the Krzysik (1974) and Vorreiter (1949) equations may be used to assess changes in the dimensions of elements in intermediate directions. The discrepancies between the experimental and theoretical values are smaller for the unit swelling values calculated with the Vorreiter (1949) equation compared to the Krzysik (1974) equation.

Keywords: swelling, calculated swelling, swelling anisotropy coefficient, wood

INTRODUCTION

As a result of absorbing moisture, wood swells, changing its linear dimensions and volume. The amount of swelling depends on the species of wood (Halász et al. 1989) its density (Kollmann 1982, Sell 1997) and chemical composition (Sjölund 2015, Prosinski 1969). For European species in the range from 0% to near 20% moisture content, the increase in swelling has a linear pattern followed by a decrease in increment size and at moisture contents above the fibre saturation point is a constant value.

The changes taking place are influenced by the anatomical direction of the wood. It was assumed that the correlation between linear swelling in the three basic directions can be expressed by the ratio, for coniferous wood 1: 10.7: 21.1 and for deciduous wood 1: 14.0 20.1, corresponding to the relationship between the longitudinal direction αl and the radial αr and tangential α_t (Mörath 1932, Kollmann 1951, 1981, Bosshard 1956, Knigge et al. 1966).

The linear swelling of European species of wood in the direction along the fibres ranges from 0.05% to 0.7% and is usually neglected due to its low value.

Swelling in the radial direction, measured perpendicular to the annual growth rings, depends in addition to all the factors mentioned above also on the width of the annual growth rings (Mörath 1932, Vorreiter 1949) and the structure of the wood cell structures (Frey-Wyssling 1940, Kollmann 1981, Walker 2006, Lanvermann 2014, Burgert 2015). For coniferous wood, swelling in the radial direction ranges from 2.2%÷2.4% to 5.1÷5.2% and for deciduous wood from 1.2%÷3.0% to 8.5%÷11.0%.

The highest values are recorded for swelling in the tangential direction, which for coniferous wood ranges from 4.0%÷7.6% to 9.0%÷15.0% and for deciduous wood from 3.0%÷5.1% to 15.0%÷16.0% and more. The amount of swelling in this direction is also influenced by the proportions of earlywood and latewood in the annual growth. The content of resin, tannins and other by-products reduces the swelling rate (Mörath 1932, Vorreiter 1949, Kollmann 1982).

The relationship between wood density and the anisotropy coefficient, which determines unit swelling in the tangential direction α_t to the radial direction α_r, has been repeatedly analysed, among others, by Mathewson (1930), Mörath (1932), Trendelenburg (1939), Burmester (1972), and Halász et al. (1989). The correlations covered 5 ranges of wood density. For densities between 300 kg/m^3 and 500 kg/m^3, the first range, the ratio was 2.22÷1.89 (Mörath 1932), or 3.68÷1.52 (Mathewson 1930). In the following intervals, it gradually decreased and for the range e.g. from 900 kg/m^3 to 1100 kg/m^3 it equalled 1.55÷1.30 (Mörath 1932) or 1.76÷1.23 (Mathewson 1930).

In practice, in addition to determining the amount of swelling in the main anatomical directions, changes in dimensions in the intermediate directions become important. They are most often calculated on the basis of the measured swelling in the tangential and radial directions and the angle between the radial direction and the direction of annual growth rings (Keylwerth 1948, Vorreiter 1949, Krzysik 1974). In all studies it was noted that the values determined in this way are indicative (Vorreiter 1949, Krzysik 1957, 1974).

The amount of swelling is one of the important technical parameters which are taken into account in the construction of structures made of wood from different parts of the world. Differences in the properties of these species, and their different densities, affect the swelling per unit during wetting.

The study experimentally determined unit linear swelling in the tangential and radial directions and in the intermediate directions. The following wood species were selected for testing: pine – PNSY (*Pinus sylvestris L.*), oak – QCXE (*Quercus. robur L.*) and bangkirai – SHBL (*Shorea spp.*), teak – TEGR (*Tectona grandis*), merbau – INXX (*Intsia bijuga*), jatoba – HYCB (*Hymenaea courbaril L.*) (PN-EN 13556:2005). The correlation between experimental results and theoretical calculations of swelling in the intermediate directions was established.

RESEARCH MATERIAL AND METHODOLOGY

The test material consisted of samples cut from sawn wood of the following species: pine – PNSY (*Pinus sylvestris* L.) heartwood and sapwood, oak – QCXE (*Quercus. robur* L.), bangkirai – SHBL (*Shorea spp.*), teak – TEGR (*Tectona grandis*), merbau – INXX (*Intsia bijuga*), jatoba – HYCB (*Hymenaea courbaril* L.) (EN 13556:2005).

The transverse dimensions of the swelling test specimens in the tangential and radial directions were 20 mm × 20 mm and the longitudinal dimension was 10 mm (in accordance with the requirements of the PN-82/D-04111 standard). The specimens were cut while maintaining the dimensions, at angles of inclination of the annual growth rings to the radial direction equal to: 0°, 30°, 45°, 60° and 90°. Swelling measurements were taken for each species of wood in 4 groups (20 samples each) formed according to the angle of inclination of the annual growth rings.

The samples were dried to absolutely dryness (PN-77/D-04100) and then their dimensions and density were determined (PN-77/D-04101).

The swelling test was carried out in accordance with the PN-82/D-04111 standard, measuring with an accuracy of 0.01 mm after 2 and 24 hours of wetting in water. At the same time, the samples were weighed using a laboratory balance with an accuracy of 0.01 g.

The moisture content of the wood after 2 and 24 hours was determined using the following formula (PN-77/D-04100):

$$W = \frac{m_1 - m_0}{m_0} \cdot 100\ (\%) \qquad (1)$$

where:
m_1 – mass of the wood after a given wetting time,
m_0 – the absolutely dry mass of the wood.

The unit swelling was calculated in the radial and tangential directions and in the intermediate directions using following the formula:

$$\alpha_{r(t)} = \frac{a_1 - a}{a} \cdot 100\ (\%) \qquad (2)$$

where:
$\alpha_{r(t)}$ – unit linear total swelling in radial, tangential and intermediate directions (%),
a_1 – dimension of wet wood sample (mm),
a – dimension of the wood sample in absolutely dry condition (mm).

For swelling of wood in intermediate directions, the obtained experimental results were compared with theoretical calculations according to the equations given by Krzysik (1957, 1974) and Vorreiter (1949).

The swelling depending on the angle of the annual growth rings to the radial direction was calculated from the equation (Krzysik 1957, 1974):

$$\propto_{\varphi} = \alpha_r \cdot \cos^2 \varphi + \alpha_t \cdot \sin^2 \varphi \qquad (3)$$

as well as from the equation (Vorreiter 1949):

$$\propto_{\varphi} = \alpha_r \cdot \alpha_t \cdot \sqrt{\frac{1}{{\alpha_t}^2 - \sin^2 \varphi \cdot ({\propto_t}^2 - {\propto_r}^2)}} \cdot 100\ (\%) \qquad (4)$$

where:
$\propto_{\varphi}$ – swelling in the intermediate direction (%),
φ – the angle of deviation of the annual growth rings measured from the radial direction.

The density-dependent anisotropy coefficient ε, which determines the unit swelling in the tangential direction α_t to the swelling in the radial direction α_r, was also calculated (Mörath 1932, Kollmann 1945):

$$\varepsilon = \frac{\alpha_t}{\alpha_r} \qquad (5)$$

The experimental results were statistically evaluated by calculating the arithmetic mean, standard deviation and the coefficient of variation (Wieczorkowska 2004).

RESULTS AND ANALYSIS

Wood species with density in the ranges of 300÷500 kg/m^3, 500÷700 kg/m^3 and over 700 kg/m^3 were selected for testing of unit swelling changes in the tangential and radial directions as well as in the intermediate directions. The first group included pine – PNSY (*Pinus sylvestris L.*) sapwood and heartwood, the second: oak – QCXE (*Quercus. robur* L.) and teak – TEGR (*Tectona grandis*), and the third: bangkirai (SHBL) (*Shorea spp.*), merbau – INXX (*Intsia bijuga*) and jatoba – HYCB (*Hymenaea courbaril L.*). The samples of each wood species were characterised by uniform density with a low coefficient of variation ranging from 3.1% to 6.2%, and in the case of teak (TEGR) 11.1% (Tab. 1).

Table 1. Density in absolutely dry state of selected wood species

Density group (kg/m^3)	Wood species	PN-EN 13556:2005	Density (kg/m^3)	V (%)
300 ÷ 500	Pine sapwood	PNSY	386	*6.2*
	Pine heartwood		487	*4.3*
500 ÷ 700	Oak	QCXE	609	*3.1*
	Teak	TEGR	647	*11.1*
700 and above	Bangkirai	SHBL	707	*3.9*
	Merbau	INXX	736	*3.7*
	Jatoba	HYCB	752	*6.3*

The absolute moisture content of the tested wood species after 2 h and 24 h of wetting in water is presented in Fig. 1.

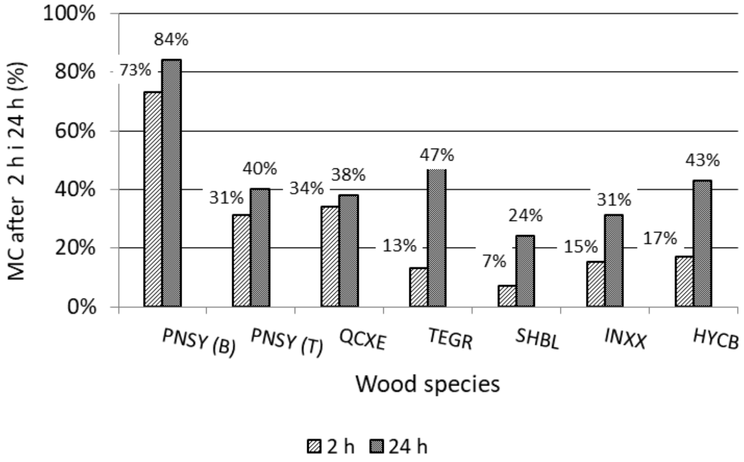

Figure 1. The moisture contents of selected wood species after 2 h and 24 h of wetting in water

The moisture content of SHBL (bangkirai), TEGR (teak), HYCB (jatoba) wood after 2 h of water exposure ranged from 7% to 17%. After 24 h there was a further increase in moisture content which ranged from 24% to 47%. The highest change in moisture content was recorded for TEGR (teak) at over 34 percentage points and a slightly lower one of 26 percentage points for HYCB (jatoba). After 24 h, an increase in moisture content close to 16 percentage points was achieved by SHBL (bangkirai) and INXX (merbau). In the case of humidifying PNSY (pine) sapwood and heartwood, and QCXE (oak), high moisture contents were found already after 2 h wetting in water, which did not change significantly during further wetting. Pine sapwood reached a moisture content of 73% after 2 h, increasing by 1 percentage points after 24 h of wetting. The difference in moisture content between 2 h and 24 h of pine heartwood was 8 percentage points, changing from 32% to 40%. The wetting of QCXE wood (oak) followed a similar pattern. The increase in moisture content after 2 h of wetting was significant and equalled 34%, changing after 24 h by only 4 percentage points (Fig. 1).

The values of the average unit swelling in the radial (0°) and tangential (90°) directions and at angles of inclination to the radial direction equal to 30°, 45° and 60°, after 2 h and 24 h of wetting in water, are shown in Tables 2 and 3.

Table 2. Unit swelling depending on the angle of inclination of the growth rings to the radial direction after 2 hours of wetting with water of selected wood species

φ	Unit swelling after 2 h (%). Experimental studies						
	PNSY		QCXE	SHBL	INXX	TEGR	HYCB
	Sapwood	Heartwood					
0°	4.86	3.24	3.56	1.22	1.71	1.07	2.20
V (%)	*3.88*	*8.50*	*8.50*	*25.18*	*8.09*	*27.09*	*8.22*
30°	5.94	4.09	3.77	1.32	1.37	1.24	2.55
V (%)	*8.01*	*19.64*	*9.40*	*21.84*	*19.35*	*14.26*	*13.70*
45°	7.27	4.46	4.11	1.87	1.52	1.41	3.64
V (%)	*8.85*	*13.81*	*3.90*	*18.25*	*17.65*	*13.20*	*14.14*
60°	8.03	5.09	5.22	2.03	1.78	1.62	4.01
V (%)	*3.03*	*16.75*	*7.30*	*27.63*	*19.35*	*14.58*	*9.96*
90°	9.59	6.73	9.70	2.28	2.96	2.24	5.29
V (%)	*4.15*	*9.95*	*10.30*	*31.26*	*12.78*	*27.15*	*13.56*

The study showed that radial swelling measured perpendicularly to the annual growth rings depends primarily on the species of wood. After a short time of wetting, the swelling of pine and oak was very high in comparison with the swelling of the other species.

Table 3. Unit swelling depending on the angle of inclination of the year rings to the radial direction after 24 hours of wetting in water of selected wood species

φ	Specific swelling after 24 h (%). Experimental studies						
	PNSY		QCXE	SHBL	INXX	TEGR	HYCB
	Sapwood	Heartwood					
0°	4.87	4.46	3.89	3.73	2.32	2.45	4.51
V (%)	*3.68*	*9.35*	*9.30*	*9.74*	*10.92*	*12.8*	*5.98*
30°	6.03	5.37	4.44	5.75	2.70	3.05	5.36
V (%)	*4.29*	*16.02*	*7.70*	*16.15*	*16.42*	*9.27*	*5.34*
45°	7.26	5.90	5.23	6.34	3.09	3.96	6.27
V (%)	*10.52*	*15.21*	*4.40*	*10.93*	*18.35*	*10.37*	*19.69*
60°	8.71	7.00	6.06	8.42	3.78	5.01	7.46
V (%)	*3.71*	*16.02*	*5.90*	*20.06*	*16.75*	*8.18*	*11.08*
90°	9.63	7.52	11.65	9.60	4.47	5.79	8.51
V (%)	*3.57*	*15.21*	*11.00*	*3.63*	*11.92*	*4.05*	*11.67*

Pine wood, both sapwood and heartwood, reached maximum swelling already after 2 h of wetting in water, and further wetting changed their dimensions within a fraction of a percent (Tables 2 and 3). Similar variation in swelling after 2 h and 24 h of wetting, amounting to less than 1 percentage point, was shown by oak wood.

For the other wood species, the unit swelling in the radial direction after 2 h of wetting was low and ranged from 1.07% (TEGR) to 2.20% (HYCB). In this case, the increase in swelling was directly related to the increasing density of the wood (Table 1) and the moisture content obtained after this time ranging from 7% to 17% (Fig. 1). A different pattern of dimensional changes was observed after 24 h of wetting in water. Merbau (INXX) and teak (TEGR) showed the lowest swelling, not exceeding 2.5%, with a difference in density of almost 90 kg/m^3 between these species (Tab. 1). In addition, after this time there was a significant increase in the moisture content of teak wood, exceeding the moisture content of the fibre saturation point (Kollmann 1981). The maximum swelling of over 4% per unit was characteristic of jatoba wood (HYCB), which had the highest density and moisture content of 43% in this group of studied species (Fig. 1).

Similarly as in the case of swelling in the radial direction, pine (PNSY) wood (sapwood and heartwood) and oak wood were characterised by significantly higher dimensional changes in the tangential direction compared to the other wood species. The maximum swelling of pine and oak wood was reached already after 2 h of wetting in water and its increase after 24 h did not exceed 2 percentage points (Tab. 2 and 3).

The unit swelling in the tangential direction after 2 h of wetting of bangkirai (SHBL), teak (TEGR), merbau (INXX), despite differences in density ranging from 647 kg/m^3 to 736 kg/m^3, ranged from 2% to 3% and was similar to swelling in the radial direction. Only the swelling of jatoba wood (HYCB) with the highest density of 752 kg/m^3 reached a value of more than 5%. After 24 h of wetting in water, the swelling per unit increased in a different way, reaching values from more than 4% to almost 10% and was strictly dependent on the species of wood and the moisture content achieved afterwards (Tab. 3).

Table 4. Swelling anisotropy coefficient ε after 2 h and 24 h of wetting in water of selected wood species

Density (kg/m^3)	Wood species	$\varepsilon=\alpha_t/\alpha_r$			
		tested		Mörath	Mathewson
		2 h	24 h	(1932)	(1930)
300÷500	PNSY (pine)				
	Sapwood	1.97	1.98	2.22÷1.89	3.68÷1.52
	Heartwood	2.08	1.69		
500÷700	QCXE (Oak)	2.72	3.00	1.92÷1.66	2.26÷1.41
	TEGR (Teak)	1.81	2.36		
700 and above	SHBL (Bangkirai)	1.87	2.57	1.75÷1.39	2.08÷1.29
	INXX (Merbau)	1.73	1.93		
	HYCB (Jatoba)	2.40	1.89		

The relationships between the unit swelling values in the tangential and radial directions obtained experimentally were confirmed by the swelling anisotropy coefficients ε presented by Mörath (1932) and Mathewson (1930) for three ranges of wood density (Tab. 4). The discrepancies concerned mainly woods with a density between 500 and 700 kg/m^3. Oak (QCXE) and teak (TEGR) wood species belonging to this group were characterised by higher swelling anisotropy values exceeding the limits determined by both authors. In the case of oak wood, the value of the anisotropy coefficient could be related to the different density of the earlywood and latewood structure in the anatomical directions studied (Kollmann 1981). The poor water absorption of teak wood tissue, presumably slowed down the swelling process, induced disproportionate dimensional changes in both radial and tangential directions and increased the anisotropy coefficient (Burmester 1972).

Bangkirai (SHBL) and jatoba (HYCB), which belong to the third group in terms of density, are also characterised by higher swelling anisotropy coefficients. These differences could be related to the non-uniform swelling in a given anatomical direction of high-density woods at a given wetting time (Burmester 1972, Kollmann 1981).

Tables 2 and 3 show the measured unit swelling in the intermediate directions after 2 h and 24 h. As the angle from 0° to 90° formed between the radial direction and the direction of the arrangement of the annual growth rings increased, the swelling gradually increased. A comparison of the experimental results with the theoretical ones, calculated in accordance with equation 3 proposed by Krzysik (1974) and equation 4 recommended by Vorreiter (1949),

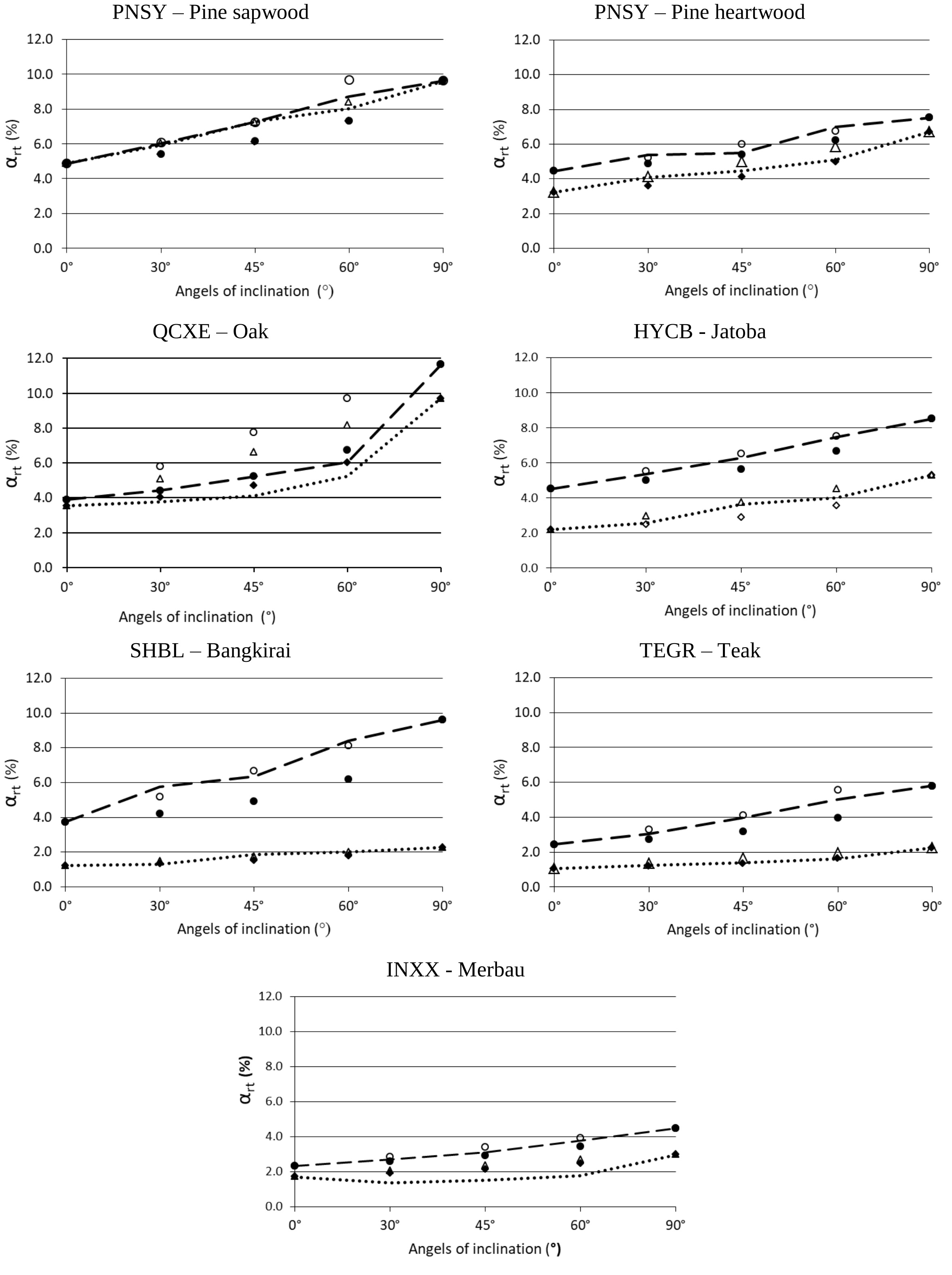

Figure 2. Unit swelling at angles of inclination of annual growth rings equal to 0°, 30°, 45°, 60° and 90° obtained experimentally (Ex) compared with calculated values according to Krzysik - 3 (1974) and Vorreiter - 4 (1949) formulae after 2 h and 24 h humidification for pine sapwood and heartwood (PNSY), oak (QCXE), jatoba (HYCB), bangkirai (SHBL), teak (TEGR), merbau (INXX).

The swelling values obtained from the experiment were lower than those calculated by equation 3 and higher than those calculated by equation 4. The deviations between the calculated values and the measurements increased as the angle of inclination of the annual growth rings increased.

The differences resulting from calculations according to equation 3 reached up to 1.5 percentage points and reflected the essence of changes in the dimensions of the examined wood species both after 2 h and 24 h of wetting. The exception was oak wood (QCXE), for which the scatter between calculations and measurements was higher and at an angle of 60° after 2 h amounted to 3, and after 24 h almost 4 percentage points.

The results of unit swelling calculations obtained according to equation 4 were lower than the experimental ones by about 1 percentage point after both wetting times. Exceptions included pine (PNSY) sapwood and bangkirai (SHBL), for which, at an angle of 60° after 24 h, the calculated difference was more than 2 percentage points. Some deviation for these calculations was also noted for oak (QCXE) and merbau (INXX), showing higher swelling after 2 h, varying by no more than 1 percentage point.

The swelling values calculated with the equations according to Krzysik (1974) and Vorreiter (1949) show that both equations may be used to evaluate changes in the dimensions of elements with cross-sections characterised by deviations of annual growth rings from the radial and tangential directions. Vorreiter (1949) equation determines swelling with higher accuracy. Although in this case the results are underestimated, they correctly characterise the change of dimensions for wood species with heterogeneous structure in a wide density range. In the case of calculations according to the Krzysik equation (1974), the calculated values are overestimated in comparison with those obtained experimentally with differences reaching up to several percentage points.

CONCLUSIONS

The results of the research and analysis carried out allow the following conclusions to be drawn:

1. In spite of diversified density in three ranges: 300÷500 kg/m^3 and 500÷700 kg/m^3 and over 700 kg/m^3, the unit swelling of the investigated wood species after 2 h and 24 h of wetting in water showed the lowest value in the radial direction (0°), which increased with the angle of inclination of annual growth rings and, after reaching 90°, corresponded to swelling in the tangential direction.
    - Pine (PNSY) sapwood and heartwood and oak (QCXE) wood after a wetting time of 2 had the highest swelling per unit, with slight changes during further wetting up to 24 h.
    - Swelling increments for the tested wood species from the other density ranges were lower and after 2 h of wetting ranged from 1% to more than 2% in the radial and tangential directions, respectively, thus showing a slight increase in their dimensions in both directions. Significant changes occurred only after 24 h of wetting. Swelling in the radial direction ranged from over 2% (teak, merbau) to over 4% (jatoba). In the tangential direction, the increase in swelling was mainly up to almost 10% for bangkirai (SHBL) and jatoba (HYCB), while for merbau (INXX) it was 4.5%, and 5.8% for teak (TEGR). For high-density woods, it seems necessary to extend the wetting time to more than 24 h (PN-82/D-04111) to determine the maximum unit swelling.
2. The swelling anisotropy coefficients ε of the studied wood species correspond to the values available in the literature. The discrepancies concern mainly the wood of oak (QCXE) and teak (TEGR) after 24 h of wetting, and they significantly exceed the ranges of changes foreseen for the species with density mixing in the range 500÷700 kg/m^3. After 2 h and 24 h of wetting, there were also slight differences in the

case of bangkirai (SHBL) and jatoba (HYCB), both belonging to the third density range, due to the uneven swelling pattern in the tested directions.

3. The values of unit swelling in the intermediate directions calculated with the equations of Krzysik (1974) and Vorreiter (1949) can be used to evaluate changes in the dimensions of components during wetting. There is less discrepancy between experimental and theoretical values of swelling calculated with the Vorreiter (1949) equation compared to the Krzysik (1974) equation.

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Streszczenie *Wpływ układu słojów rocznych na spęcznienie wybranych gatunków drewna.* Zbadano spęcznienie jednostkowe w kierunku promieniowym i stycznym drewna o gęstości, zawierającej się w trzech przedziałach 300÷500 kg/m^3 i 500÷700 kg/m^3 oraz powyżej 700 kg/m^3, do których należały sosna – PNSY (*Pinus sylvestris* L.*)*, dąb – QCXE (*Quercus. robur* L.*)* oraz bangkirai – SHBL *(Shorea spp.),* teak – TEGR (*Tectona grandis),* merbau – INXX (*Intsia bijuga),* jatoba – HYCB *(Hymenaea courbaril* L). Dla wszystkich badanych gatunków drewna stwierdzono, najniższe spęcznienie w kierunku promieniowym (0°) zarówno po 2 h i 24 h nawilżania w wodzie, które rosło wraz z kątem nachylenia przyrostów rocznych i po osiągnięciu 90°, odpowiadającemu kierunkowi stycznemu, osiągnęło maksymalna wartość. W przypadku drewna sosny (PNSY) biel i twardziel oraz drewna dębu (QCXE) po czasie nawilżania równym 2 h uzyskano maksymalne spęcznienie jednostkowe, niezmieniające się po 24 h nawilżania. Przyrosty spęcznienia dla pozostałych gatunków drewna były niższe i po czasie nawilżania 2 h wynosiły od 1% do ponad 2%, wykazując nieznaczne różnice między kierunkami promieniowym i stycznym. Po 24 h nawilżania spęcznienie było wyższe i w kierunku promieniowym wahało się od ponad 2% do blisko 5% a w kierunku stycznym od ponad 4% do 10%. W przypadku drewna o wysokiej gęstości wydaje się konieczne wydłużenie czasu nawilżania, który pozwoli na ustalenie rzeczywistego maksymalnego spęcznienia jednostkowego. Współczynniki anizotropii spęcznienia α badanych gatunków drewna odpowiadają wartościom zawartym w literaturze przedmiotu. Wyższe współczynniki wykazały dąb (QCXE) i teak (TEGR), bangkirai (SHBL) i jatoba (INXX), związane z charakterystycznymi cechami struktury gęstości i budowy anatomicznej. Obliczone równaniami Krzysika (1974) i Vorreiter (1949) wartości spęcznienia jednostkowego mogą służyć do oceny zmian wymiarów elementów w kierunkach pośrednich, powstałych w wyniku nawilżania. Mniejsze rozbieżności między wartościami eksperymentalnymi i teoretycznymi wykazują spęcznienie jednostkowe obliczone równaniem Vorreitera (1949) w porównaniu z równaniem Krzysika (1974).

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