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Variability in density of spruce (*Picea abies* [L.] Karst.) wood with the presence of reaction wood

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ABSTRACT: The study was aimed to assess the integral value that determines wood properties – wood density at a moisture content of 0% and 12%. The wood density was researched in a sample tree with the presence of reaction compression wood. The density was determined for individual zones (CW, OW, SWL and SWR). The zone where compression wood (CW) is present has a higher density than the remaining zones. On the basis of the acquired data, 3D models were created for individual zones; they describe the variability of wood density along the stem radius and stem height. The influence of the radius seems to be a statistically highly significant factor. The wood density is significantly higher in samples with the presence of compression wood. When the proportion of compression wood in the sample was 80%, the wood density was 1.5 times higher compared to wood without compression wood.

Keywords: spruce; density; compression wood

Wood properties are a result of chemical composition and wood structure on all its levels, i.e. submicroscopic, microscopic and macroscopic ones. Density is considered to be the most significant wood property that also strongly affects the other physical and mechanical wood properties. Therefore, it is this physical property that has always been paid the greatest attention.

Genetic features (species and genus), environmental factors (soil, climatic conditions, position, mechanical forces such as wind and snow), physiological and mechanical effects (age, tree height, form and height of the tree crown, position of the tree in the stand) operate simultaneously, influencing the character and the organization of individual anatomical elements, including varying wood density (Trendelenburg 1939). Spruce wood density ranges between 370 and 571 kg/m^3 (when ρ_0). Wood density and its variability in relation to various factors were discussed by several authors (Gindl, Teischinger 2003; Niemz, Sonderegger 2003; Perstorper et al. 2001; Merforth 2000; Grammel 1990; Petty et al. 1990; Kommert 1987; Bernhart 1964; Janota, Kripeň 1960; Mozina 1960; Palovič, Kamenický 1961).

Reaction wood is formed in trees, branches and roots that grow obliquely. Reaction wood in coniferous wood is formed at the bottom of bent trees and it is called compression wood (Timell 1986). Compression wood is clearly distinguishable from the surrounding wood for its dark colour. Another obvious macroscopic sign of the presence of compression wood is pith eccentricity and the resulting larger width of growth rings in the area of compression wood (Gryc, Holan 2004; Timell 1986). On the microscopic level, it is possible to observe the round section of tracheids, thicker cell walls, formation of intercellular spaces and shorter compression tracheids (Gryc, Horáček 2005; Wagenführ 1999; Nečesaný 1955, 1956).

When compared to standard wood, the compression wood density is considerably higher, the main factor being the presence of thick-walled compression tracheids in the zone of compression wood. A difference between standard wood and compression wood is dependent on the compression wood type (Timell

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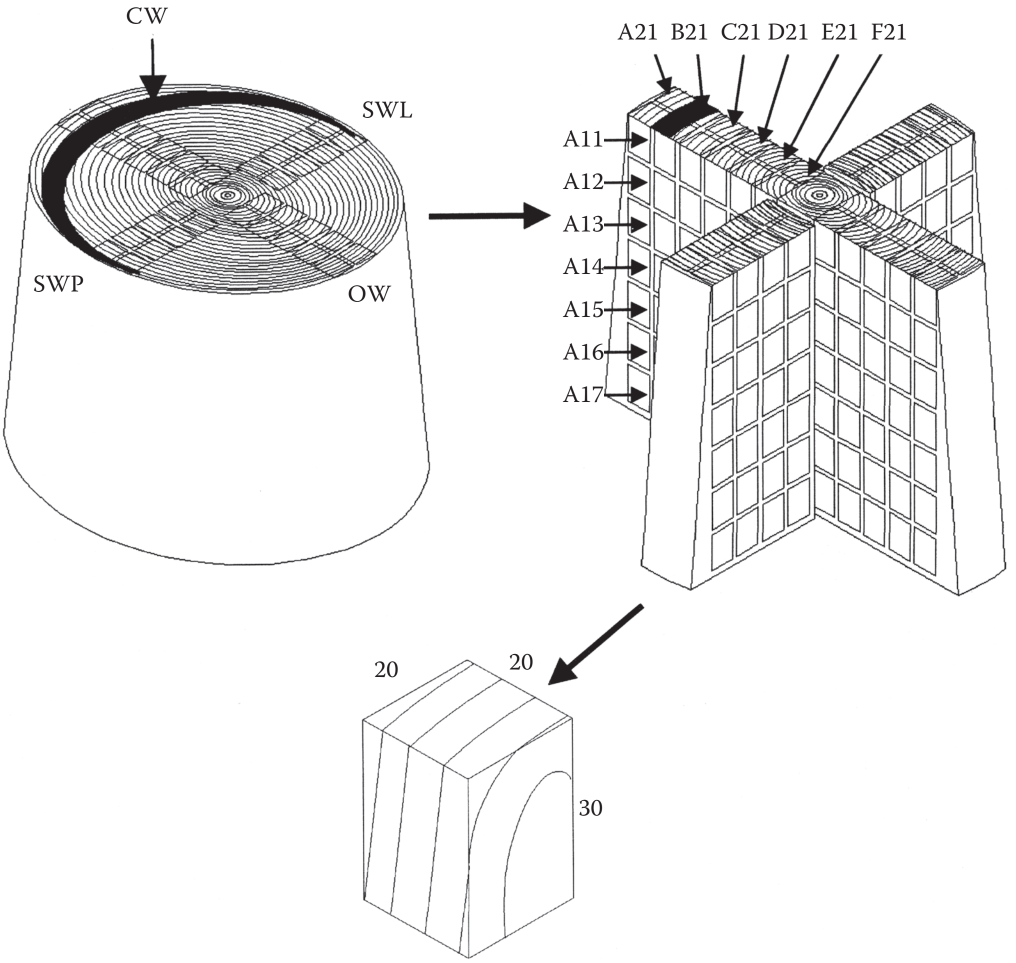

Fig. 1. The diagram of sample production out of the log and the dimensions of a sample (CW – compression zone, OW – opposite zone, SWL and SWR – side zones)

1986). Table 1 shows the comparison of compression wood density and standard wood density.

This paper aims to evaluate the integral value that determines wood properties – wood density at a moisture content of 0% and 12% in relation to the position in the stem. Wood density will be researched in the compression zone (compression wood), opposite zone (opposite wood) and side zones (side wood). Further, we will research the influence of ring width and the influence of the presence of compression wood on density.

MATERIAL AND METHODS

We selected a sample spruce (*Picea abies* [L.] Karst.) tree where we anticipated the presence of reaction wood. The tree was selected in the Křtiny Training Forest Enterprise Masaryk Forest – Mendel University of Agriculture and Forestry Brno, Forest District Habrůvka, area 164 C 11. The average annual temperature in this locality is 7.5°C and the average annual precipitation is 610 mm.

The tree stem axis was diverted from the direction of the gravity. The axis was diverted in one plane only and the diversion angle at the stem basis was 21°C. The tree was 110 years old and its total height was 33 m.

Logs (20 cm high) were taken at various heights (6, 8, 10, 12, 15, 18, 20 and 22 m) and the directions of measurements were marked on them. Then, blocks of wood were sawn out of the logs for individual

Table 1. The density of compression (CW) and opposite (OW) spruce wood according to various authors

CW density (kg/m^3)	OW density (kg/m^3)	Moisture content (%)	References
436	420	0	Seeling (1999)
471–560	460	12	Kučera (1973)
766–795	405–439	0	Rak (1957)
452	423	0	Trendelenburg (1932)

zones (a block of CW – compression wood zone, a block of OW – opposite zone, and two blocks from side zones, i.e. SWL and SWR). The blocks were dried in the chamber kiln until the final 8% wood moisture content was reached. After drying, samples of these dimensions were made: 30 ± 0.5 mm long, 20 ± 0.5 mm wide and 20 ± 0.5 mm thick (Fig. 1). It was necessary that the samples would be of a special orthotropic shape. The maximum allowed divergence of rings was set to 5° for testing, the maximum allowed divergence of fibres was also set to 5°. Each sample was marked so that an exact identification of the position in the stem was later possible.

The marked samples were put in the kiln where they were dried at the constant temperature of 103 ± 2°C until absolutely dry. Then the samples were weighed and measured so that the wood density at the moisture content of 0% could be assessed. Later, the samples were conditioned to the moisture content of 12% and they were weighed and measured again (assessing ρ_{12}). The wood density (kg/m³) at the 0% and 12% moisture content was calculated according to this formula:

$$\rho_w = \frac{m_w}{V_w}$$

where: m_w – sample weight at w = 0% and w = 12% (kg),
V_w – sample volume at w = 0% and w = 12% (m³).

To define the influence of the compression wood presence in the sample on wood density, the sample fronts were digitalized using an EPSON scanner (Epson Perfection 1660 Photo). The parameters of scanning were: colour image at 600 dpi resolution. The digital images of the fronts were used in LUCIA application. The application defined the spot where

Table 2. Descriptive statistics of the wood density for individual heights and zones

Height (m)	Statistical variable	Zone									
		CW		CW/CW		OW		SWL		SWR	
		ρ_0	ρ_{12}	ρ_0	ρ_{12}	ρ_0	ρ_{12}	ρ_0	ρ_{12}	ρ_0	ρ_{12}
22	Mean (kg/m³)	499.44	525.10	529.89	559.51	488.47	530.81	462.44	491.55	451.41	478.62
	Variance (kg/m³)²	1,064.84	1,385.41	89.71	145.89	232.71	164.00	154.49	166.03	38.91	42.22
	Coefficient of variation (%)	6.53	7.09	1.79	2.16	3.12	2.41	2.69	2.62	1.38	1.36
20	Mean (kg/m³)	461.85	490.51	461.94	491.41	457.66	497.07	456.60	482.67	467.62	495.08
	Variance (kg/m³)²	1,105.04	1,187.81	1,324.50	1,415.19	172.92	248.25	255.08	305.55	5.82	14.64
	Coefficient of variation (%)	7.20	7.03	7.88	7.66	2.87	3.17	3.50	3.62	0.52	0.77
18	Mean (kg/m³)	466.89	486.55	492.70	507.73	452.66	492.65	458.89	493.33	461.93	489.66
	Variance (kg/m³)²	2,178.00	1,219.37	2,707.25	670.62	576.51	541.11	103.64	154.73	150.23	182.87
	Coefficient of variation (%)	11.17	7.18	10.56	5.10	5.30	4.72	2.22	2.52	2.65	2.76
15	Mean (kg/m³)	450.48	478.58	477.82	507.35	442.59	478.38	444.94	476.87	480.15	501.14
	Variance (kg/m³)²	1,694.93	1,899.33	562.50	656.19	1,201.16	1,245.08	1,253.63	1,555.06	113.38	90.72
	Coefficient of variation (%)	9.14	9.11	4.96	5.05	7.83	7.38	7.96	8.27	2.22	1.90
12	Mean (kg/m³)	448.89	477.19	504.70	536.68	444.11	474.82	451.12	477.95	448.95	472.31
	Variance (kg/m³)²	4,053.20	4,807.05	3,097.79	4,088.47	2,053.67	2,181.37	1,266.61	1,510.29	2,108.15	1,970.97
	Coefficient of variation (%)	14.18	14.53	11.03	11.91	10.20	9.84	7.89	8.13	10.23	9.40
10	Mean (kg/m³)	433.79	460.63	524.86	561.12	431.96	463.96	414.74	439.55	455.02	476.96
	Variance (kg/m³)²	3,713.63	4,537.62	1,209.54	1,645.10	2,357.92	2,255.03	1,268.83	1,578.25	2,956.05	3,066.94
	Coefficient of variation (%)	14.05	14.62	6.63	7.23	11.24	10.24	8.59	9.04	11.95	11.61
8	Mean (kg/m³)	467.72	495.79	568.44	609.08	423.80	453.06	461.12	484.12	449.51	473.99
	Variance (kg/m³)²	6,514.33	8,139.14	564.35	742.51	2,291.22	2,207.16	2,072.91	2,079.60	2,904.83	2,949.37
	Coefficient of variation (%)	17.26	18.20	4.18	4.47	11.29	10.37	9.87	9.42	11.99	11.46
6	Mean (kg/m³)	471.42	498.57	579.49	620.80	437.18	458.40	447.92	468.57	432.10	454.21
	Variance (kg/m³)²	9,649.97	2,294.88	2,916.07	3,788.62	2,956.32	2,805.13	3,411.63	3,389.61	2,509.01	2,723.32
	Coefficient of variation (%)	20.84	22.24	9.32	9.91	12.44	11.55	13.04	12.42	11.59	11.49
Σ	Mean (kg/m³)	461.32	488.35	516.58	549.08	442.15	474.08	450.72	476.27	445.45	468.58
	Variance (kg/m³)²	5,059.56	6,052.94	5,470.25	6,836.22	1,936.72	2,084.07	2,189.35	2,326.14	3,393.50	3,652.89
	Coefficient of variation (%)	15.42	15.93	14.67	15.06	9.95	9.63	10.38	10.13	13.08	12.9

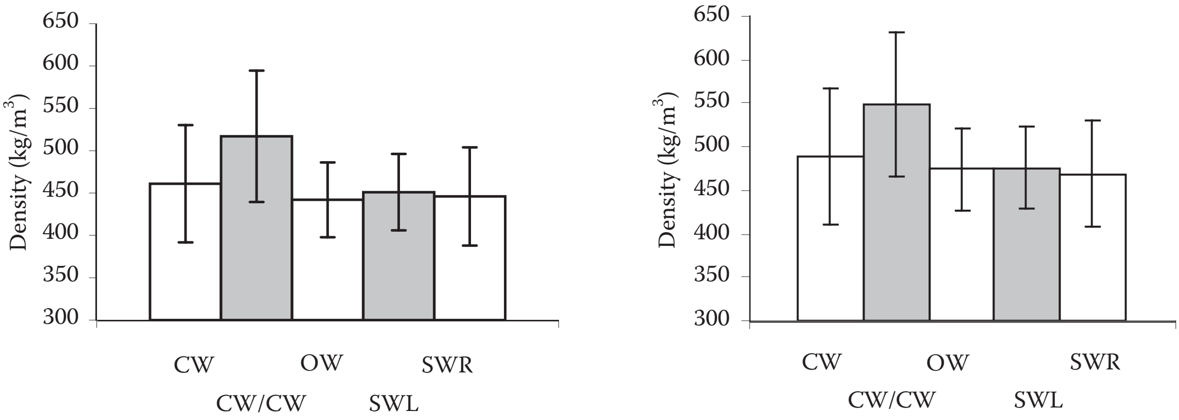

Fig. 2. Box graph, wood density (kg/m^3) at a 0% (A) and 12% (B) moisture content for individual stem zones

compression wood was present. It compared the entire sample area with the defined compression wood. The proportion of pixels with compression wood in the entire image gave us the final result of the proportion of compression wood in the sample. The samples from the CW zone which contained min. 25% of compression wood are marked as data file CW/CW in calculations.

The average ring width in the sample was set in compliance with ČSN 49 0102 standard. The width was measured using a stereo magnifier (Nikon SMZ 660).

RESULTS

Wood density was determined for the moisture content of 0% and of 12%. Detailed descriptive statistics of wood density in relation to the position in the stem (height, zones) are shown in Table 2. The wood density is represented in Fig. 2 by a box graph.

Table 3. The results of Tukey's method of multiple comparison of wood density at a moisture content of 12% ($P < 0.05$ statistically significant difference, $P > 0.05$ statistically insignificant difference)

Zone	CW	OW	SWL	SWR
CW		0.0183	0.2098	0.1727
OW	0.0183		0.9111	0.9639
SWL	0.2098	0.9111		0.9984
SWR	0.1727	0.9639	0.9984	

The graph clearly shows that the density differences in the OW, SWL and SWR zones are minimal. The density in these zones ranges between 469 and 476 kg/m^3 when the moisture content is 12%. However, the density is higher in the CW zone, where it reaches 488 kg/m^3. The compression wood density (CW/CW; only the samples containing at least 25% of compression wood were included in the calculation) is considerably higher and its value is 549 kg/m^3.

Statistical comparison of individual zones shows that there is a statistically significant difference in wood density only between the mean values of CW and OW sets. No statistically significant differences were confirmed in the other zones (Table 3). Further, the statistical research shows that the influence of the position in the stem, i.e. the radius and the height, on wood density is statistically significant (the statistical research was done for ρ_{12} only).

In the CW zone, the heights of 22 m and 10 m showed a more statistically significant variance in the mean value. In the OW zone, the same is valid for heights 22 m, 20 m, 8 m and partially also for 18 m and 6 m. In the SWL zone, only the height of 10 m showed a statistically significant difference. In the SWR zone, the ANOVA confirmed the influence of the height on wood density, but when Tukey's method of multiple comparison was used, no statistically significant influence between the individual heights was proved.

Table 4. The resulting functions for the wood density model dependent on the growth ring width

Zone	Function	Coefficient of determination		Coefficients	
		sampling	basis	a	b
CW	$y = a + bx^2\ln x$	0.40	0.39	527.25	–4.16
OW	$y = a + b\ln x$	0.74	0.74	511.75	–57.27
SWL	$y = a + bx\ln x$	0.53	0.52	502.76	–16.49
SWR	$y = a + bx^2\ln x$	0.59	0.59	499.03	–3.92

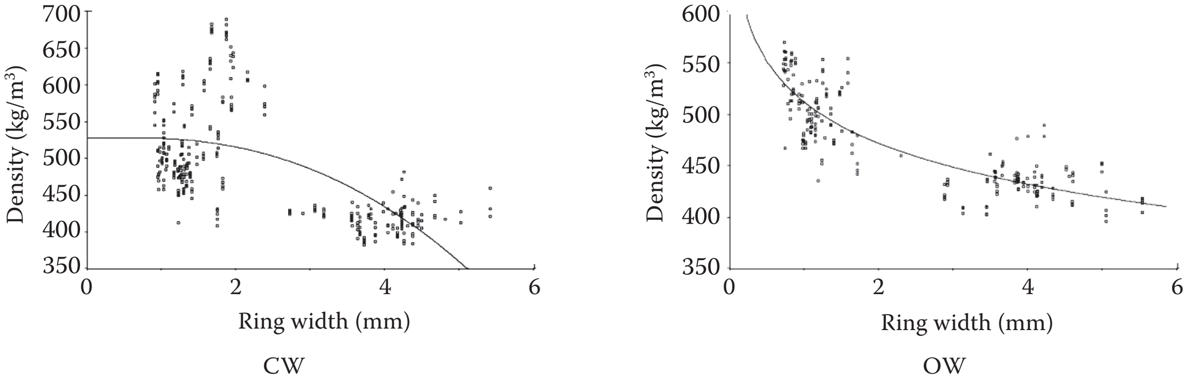

Fig. 3. The influence of ring width on wood density (w = 12%) for individual stem zones

The influence of the radius on wood density seems to be more considerable. In all zones, there were no statistical differences in wood density in the samples from the pith area, or in the peripheral areas. However, there were statistically significant differences between the other samples (along the stem radius).

The ring width is an important parameter influencing the density of spruce wood. The influence of the ring width on wood density at a 12% moisture content for individual zones is shown in Fig. 3.

Wood density was found to decrease with the increasing ring width. There are two collections of data in each model. The first collection contains samples which had wide rings and therefore low wood density. These samples were taken from the central parts of the stem, where the wood increments are the highest. The second collection contains samples with narrow rings where the wood density is considerably higher. As 2D models show, the difference is 100 kg/m^3 on average. The difference is higher (150 kg/m^3) in

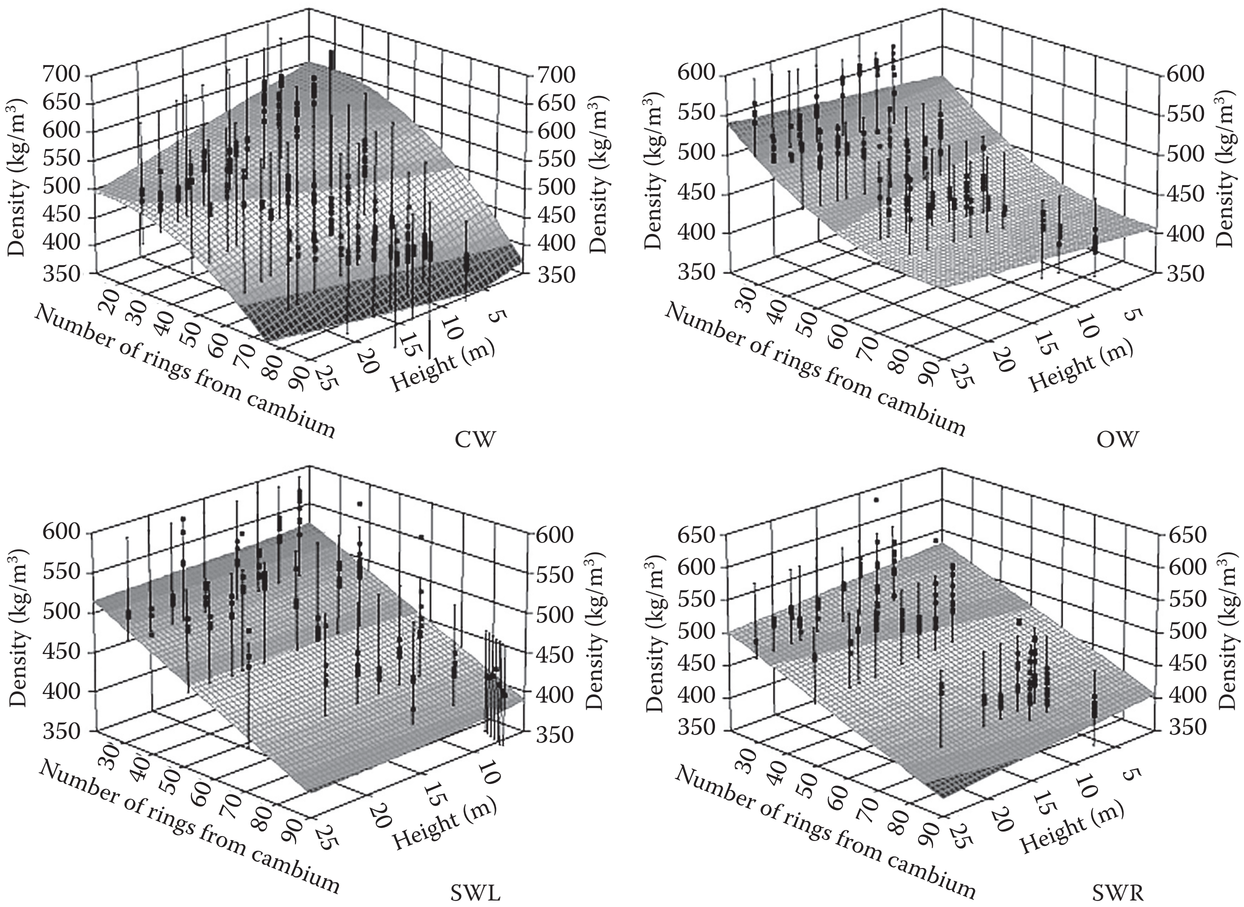

Fig. 4. Wood density (w = 12%) in relation to the position in the stem

Table 5. The resulting function for the wood density model dependent on the compression wood area in the sample

Function	Coefficient of determination		Coefficients	
	sampling	basis	*a*	*b*
$y = a + bx^2\ln x$	0.55	0.54	474.52	0.0065

Table 6. The resulting functions for the wood density (w = 12%) dependent on the position in the stem

Zone	Function	Coefficient of determination		Coefficients			
		sampling	basis	*a*	*b*	*c*	*d*
CW	$z = a + bx + cy + dy^2$	0.52	0.51	592.26	–4.27	1.27	0.04
OW	$z = a + bx + cy + dy^2$	0.72	0.71	587.23	1.12	–4.30	0.03
SWL	$z = a + b\ln x + cy$	0.56	0.56	572.99	–5.99	–1.93	
SWR	$z = a + bx + cy$	0.62	0.61	565.75	–1.17	–1.77	

the CW zone, which is caused by the presence of reaction compression wood. The data in the CW zone obviously correspond to wood with the presence of compression wood (1.5–2 mm ring width and 560 to 680 kg/m^3 density) (Fig. 3a). The created models and function coefficients are statistically significant. Correlation coefficients of the selected set are 0.397 up to 0.739, which demonstrates a medium up to a strong dependence of wood density on the ring width (see Table 6).

3D models were created using all the data acquired by measuring; the models describe the influence of stem radius and height on wood density (Fig. 4). There is an obvious remarkable increase in wood density along the stem radius in all the models. In the CW zone, the increase is more distinct in the first 40 years of growth, then the wood density stagnates. In the other zones, i.e. OW, SWL and SWR, the increase is constant along the entire stem radius. The remarkable influence of the stem radius on wood density corresponds with the statistical results of ANOVA.

Wood density decreases in the CW zone with the increasing height. In the side zones SWL and SWR it is also possible to see a gradual decrease in density with the increasing stem height. Only the model for the OW zone shows an opposite trend. However, looking closely at the model, we can see the values measured at various heights are not significantly different. The reverse trend in this zone can be caused by the fact the data from lower positions in the stem are missing. To sum up, the insignificance of the wood density changes along the stem height in our models is again a confirmation of the statistical results of ANOVA. The created functions and equation coefficients valid for the description of the wood density variability in relation to the position in the stem are shown in Table 6. The marked influence of the position in the stem on wood density was confirmed by high correlation coefficients of the selected sets (0.517 up to 0.718).

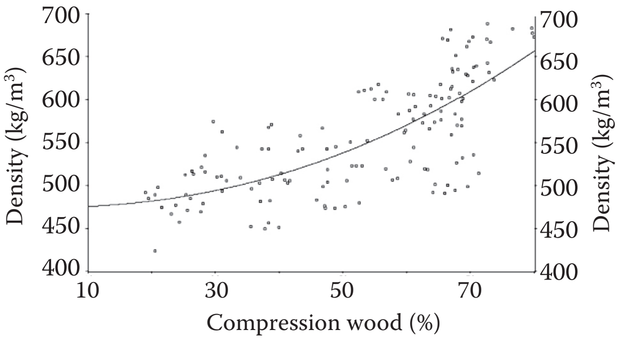

Fig. 5. The influence of compression wood on wood density (w = 12%)

When the macroscopic and microscopic structure changes, considerable changes in properties, in our case in wood density, can also be expected. Fig. 5 clearly shows a trend when density increases with the increasing percentage of compression wood in the sample. When there is 10% of compression wood in the total area of the sample front, the wood density is 475 kg/m^3, which is a value similar to the density of standard wood. When there is 80% of compression wood in the front, the density is 680 kg/m^3, in other words, it is 1.5 times higher. The created model that describes the influence of compression wood on density was statistically significant and the high values of correlation coefficients confirm the statistically significant relation between the researched values. The function describing the relation between the density and the proportion of compression wood, the correlation coefficients and equation coefficients are represented in Table 5.

DISCUSSION

The change in the wood density variability along the stem radius is often connected with the tree age, as the cambium of older trees forms considerably narrower rings (with a high proportion of late-wood) compared to the rings in the juvenile wood area (Reck 2002; Merforth 2000; Palovič, Kamenický 1961; Trendelenburg 1939). The lowest density in the spruce wood is near the pith; then the density increases in the radial direction proportionally to the decreasing width of rings; on the periphery, in the sapwood with narrow rings, the density reaches its highest value (Lexa et al. 1952). Panshin and Zeeuw (1980) classify spruce wood as soft wood, where the density increases in the direction from the pith to the periphery, which might be caused by the growing proportion of late-wood in a ring. The authors also pointed out to the analogy between the trends of late-wood density and late-wood tracheid length, as both the values grow with the stem radius, whereas the early-wood density falls in the direction from the pith to the mature wood and then it is constant. Mitschell and Denne (1997) concentrated on the wood of Sitka spruce (*Picea sitchensis* [Bong.] Carr) and described a decrease in the density of the rings formed first. The density decreased between the second and the sixth ring from 450 kg/m^3 to 330 kg/m^3. The authors explained the decrease as a result of the increasing ring width and the larger radial dimension of tracheids.

The created 3D models (Fig. 4), which describe wood density in relation to the position in the stem, also show the increase in wood density with the stem radius. This transition can be caused both by the decrease in the ring width along the stem radius (Gryc, Holan 2004), and also by the increasing proportion of late-wood in the rings. Further, the thickness of tracheid cell walls, which grows with the increasing distance along the stem radius, can also be expected to positively influence wood density (Zobel, Sprague 1986). The models do not show a decrease in wood density near the pith, as presented by Mitschell and Denne (1997), because the wood near the pith was removed when the samples were created and because the wood density change among a few rings would be difficult to demonstrate in a 3D model.

Furthermore, considerable changes in wood density with the stem height have also been confirmed. Lexa et al. (1952) stated that even with the ring width being identical, there were lower proportions of late-wood at higher positions of the stem than at lower positions. When the rings are wider at higher positions than at lower positions, it is only natural that this is manifested by a decrease in wood density. Palovič and Kamenický (1961) also confirmed a decrease in wood density with the increasing stem height. Bosshard (1974) reported the more-or-less identical density in the spruce along the whole stem. Reck (2002) did not confirm that the wood density decreased with a higher stem.

The measurements of the sample tree proved a very gradual decrease in wood density with the increasing height in the side zones. In the CW zone, the decrease is more than apparent and it is caused by the presence of a well-developed compression zone in lower parts of the stem. In the opposite zone, the trend is reverse; however, the difference between the lower and the upper parts of the stem is very small.

Seeling (1999), Timell (1986), Seth and Jain (1978), Schulz et al. (1984), Kučera (1973), Rak (1957) and others agreed that the density of compression wood was considerably higher in comparison with opposite wood or to standard wood.

The values of compression wood density found out in the sample tree also clearly confirm higher density of compression wood, which is 550 kg/m^3 at a 12% moisture content as compared to 450 kg/m^3 in the opposite zone. The wide range of varying values of compression wood density presented by various authors was caused by different types and amounts of compression wood in the researched samples. High variability of compression wood density is shown in Fig. 5, where the variability of compression wood density was explored in relation to the area of compression wood in the sample. The range of values from 500 kg/m^3 to 700 kg/m^3 is a good example. This varying density of compression wood is caused by the presence and the amount of thick-walled compression tracheids whose cell wall thickness is considerably higher (Timell 1986) compared to the cell walls of early-wood and late-wood tracheids of standard wood.

It is obvious that reaction compression wood has a different structure from standard wood. For a modified structure we can also expect different wood properties. Compression wood has a different structure that is manifested in the researched wood property – density. When processing and using wood where compression wood is present it is necessary to expect some troubles. Because the compression wood density is higher, higher energy will be needed for any work with the material; moreover, compression wood has a different tint, which may look improper for some products unless the difference is requested. To conclude, this work was aimed and managed to expand the knowledge of the properties of Norway spruce (*Picea abies* [L.] Karst.) wood with the presence of reaction wood.

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Variabilita hustoty dřeva smrku (*Picea abies* [L.] Karst.) s přítomností reakčního dřeva

ABSTRAKT: Studie se zabývá vyhodnocením integrální veličiny určující vlastnosti dřeva – hustoty dřeva při vlhkosti 0 % a 12 %. Hustota dřeva byla zkoumána na vzorníkovém stromě s přítomností reakčního tlakového dřeva. Hustota dřeva byla stanovena pro jednotlivé zóny (CW, OW, SWL a SWR). Zóna s přítomností tlakového dřeva (CW) má vyšší hustotu než zóny zbývající. Ze získaných dat byly vytvořeny 3D modely pro jednotlivé zóny, které popisují variabilitu hustoty dřeva po poloměru a výšce kmene. Vliv poloměru se statisticky jeví jako velmi významný faktor. U zkušebních vzorků s přítomností tlakového dřeva se hustota dřeva významně zvyšuje. Při 80% podílu tlakového dřeva ve zkušebním vzorku byla hustota dřeva 1,5krát vyšší ve srovnání se dřevem bez přítomnosti tlakového dřeva.

Klíčová slova: smrk; hustota; tlakové dřevo

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