

INFLUENCE OF PRESSING PARAMETERS ON DIMENSIONAL STABILITY AND SELECTED PROPERTIES OF PRESSED BEECH WOOD. I. DIMENSIONAL STABILITY AND DENSITY

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ABSTRACT

This work was aimed at investigation of the influence of pressing parameters (pressing temperature, pressing time, compression degree) on density, hardness and dimensional stability of beech wood specimens. The specimens, with an initial moisture content of 17 %, were pressed in tangential direction. The results show that the dimensional stability significantly improved with increasing pressing temperature and time. Under the given conditions, the optimum temperature was 200 °C and the optimum heating time was 6 minutes. These pressing parameters, however, could not guarantee the appropriate dimensional stability under moisture loading.

Keywords: pressing, dimensional stability, moisture content, beech wood, temperature, pressing time, density.

INTRODUCTION

Pressing of native wood is a classic technology for waste-free wood treatment. The native wood is pressed with the purpose to increase its density, to improve its mechanical properties, and to shape its relief. The final properties of compressed wood are also significantly affected by its dimensional stability after pressing. To uphold the stability of the compressed wood means to guarantee the attained properties of the material undisturbed. The performance of compressed wood is affected by a range of factors such as wood's moisture content and temperature under pressing, pressing time, pressing pressure or the degree of compression.

The two primary factors underlying the pressed wood's density are the pressing degree and wood species (BLOMBERG *et al.* 2006). The authors report for seven wood species pressed under a constant pressure, average values (species-specific) ranging 750–1100 kg·m⁻³.

WANG and COOPER (2005) show that pressed wood exhibits non-homogeneous density patterns across the cross-cut (in pressing direction). The variable density profiles confirm that the compression of the pressed body in the pressing direction is not uniform. This is negatively reflected in the dimensional stability of the pressed wood (KÚDELA and REŠETKA 2011). There is arising a question about which pressing parameters can guarantee an appropriate dimensional stability of the pressed wood.

Former works (CHUCHRJANSKIJ 1953, STAMM and SEBORG 1941 and SEBORG *et al.* 1962) report that wood with moisture content below 13 %, pressed at 150 °C, was not stable; and after repeated wetting and heating, it returned almost to the original state. To ensure the dimensional stability of the pressed wood, the wood was fixed chemically, physically or mechanically. The mechanism, however, driving densification of hydrothermally treated wood, had not been fully recognised yet. So, there were started thorough studies of the hydrothermal treatment itself, with the purpose to attain good malleability and better stability of the compressed wood (ITO *et al.* 1998a, b, INOUE *et al.* 1998, DWIANTO *et al.* 1999, NAVI

and GIRARDET 2000, HIGASHIHARA *et al.* 2000, REINPRECHT and VIDHOLDOVÁ 2011 and others). New possibilities for exploring wood modifications induced by heat and moisture gave other incentives for re-starting the research.

ITO *et al.* (1998) obtained, after preliminary plasticization, high dimensional stability for wood pressing temperatures above 180 °C, while the wood stability was also significantly affected by pressing time at the given temperature. JOHANSSON *et al.* (2006) report that wood heat-treated at varying temperatures reached the lowest sorption capacity at 200 °C. BÄCHLE (2007) documents an even ca 50% reduction of equilibrium moisture content of wood subjected to heat treatment. Reduction of wood sorption capacity results in improving dimensional stability. INOUE *et al.* (1998) fixing pressed wood by high-frequency heating, reduced, in such a way, its instant reversible deformation significantly. High-frequency heating was used in beech wood pressing also by Közsegi *et al.* 2000. The referred works show that the wood's dimensional stability is significantly influenced by interaction between moisture content and temperature. The effect of temperature is pronounced under high moisture content.

NAVI and GIRARDET (2000) show that better results can be obtained for beech wood pressed at 150 °C in saturated steam (thermo-hydro-mechanical treatment – THM) than for the same wood pressed at low moisture contents (thermo-mechanical treatment – TM). The authors also demonstrated that, in comparison with compressed wood, THM compressed wood exhibited significantly reduced sorption capacity and better dimensional stability after repeated wetting in water. There is evidence for a range of other factors improving the dimensional stability in THM beech wood. Under given conditions, the destruction of lignin-carbohydrate matrix is more advanced, and after removal of the moisture and heat load, the matrix molecules are cross-linked due to restoration of hydrogen bonds distorted by wood plasticization and shaping. The stresses in the matrix are relaxed; the hygrophilous cell wall components (primarily hemicelluloses) form polymers showing more resistance against water. There were also observed different mechanisms driving deformation of cell elements. On the other hand, high wood moisture content has also negative impacts – and for higher pressing temperatures, a moisture content range of 15–20 % is recommended.

The results of the cited works do not allow specification of the optimum moisture content and temperature for wood during pressing, due to the influence of a range of other factors. KÚDELA (2005), CLAIR *et al.* (2003) and ESTEVES and PEREIRA (2009) show that molecular mechanisms underlying changes in wood are very diverse and complex. Several changes to wood structure have been explained satisfyingly (changes to chemical structure, degradation of hemicelluloses and of amorphous cellulose, lignin networking, reduction of the amount of hydroxyl groups followed by changes in sorption properties), many several, nevertheless, are still waiting for clarification (CLAIR *et al.* 2003).

The aim of our work was to find out, by experiments, the influence of selected pressing parameters (high temperature, varying pressing time and varying compression degree) on the density and dimensional stability of beech wood after pressing followed by conditioning to various moisture contents. Another aim was to use the obtained results for determining the optimum value of pressing temperature for the given pressing conditions.

MATERIALS AND METHODS

The experiments were carried out on beech wood test specimens with dimensions of 50 × 50 × 20 mm (R × L × T) – Fig. 1. The pressing direction was decided in accordance with CHUCHRJANSKYJ (1953), PERELYGIN (1965) and KÚDELA (1990), who report for beech wood better compressibility in tangential direction – due to a high portion of pith rays.

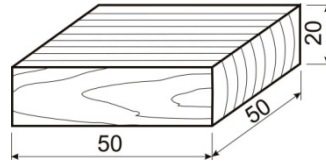


Fig. 1 Test specimen – shape and dimensions.

The test specimens were conditioned at a relative air humidity of 80 % and a temperature of 20 °C, corresponding to an equilibrium moisture content of 17 %. The acclimated specimens were pressed in testing compression equipment ZDN 50. Before the pressing, the specimens were weighed with an accuracy of 0.01 g and measured with an accuracy of 0.01 mm.

The pressing appliance was equipped with two pressing plates, with controlled heating. The heating was electric, controlled with a thermostat whose gauge was inserted directly in the pressing plate. For the pressing process, we chose four temperature regimens: 160, 180, 200 and 220 °C and three pressing periods: 2, 4 and 6 minutes. The specimens were pressed by 20 % and by 40 %. This extent was obtained with the aid of restraining metal mats with the thickness corresponding to the desired compression (20 % => 16 mm; 40 % => 12 mm).. By combining these factors, we obtained 24 different pressing regimens. For each regimen, there were used 10 specimens, altogether 240.

The conditioned specimens were taken out from the equipment, were weighed and measured with the same accuracy as above. Then they were stored in a conditioning box with a relative air humidity of 65 % and a temperature of 20 °C until reaching the equilibrium state. Further conditioning of the specimens was pursued at $\varphi = 80 \%$ and $t = 20 \text{ }^\circ\text{C}$. The conditioned specimens were weighed and measured again. Finally, the specimens were dried out to zero moisture content – to obtain the dry mass m_0 .

The dimensional change of the test specimens in the pressing direction was calculated two times: immediately after the removal from the pressing equipment, according to the equation:

$$D_1 = \frac{H_1 - H_0}{H_0} \cdot 100 \quad (1)$$

and after the conditioning of the test specimens in an environment with parameters (φ , t), according to the equation

$$D_2 = \frac{H_{2(3)} - H_0}{H_0} \cdot 100, \quad (2)$$

where H_0 is the thickness of specimen after compression (16 or 12 mm), H_1 – is the thickness of specimen taken out from the pressing equipment, $H_{2(3)}$ – is thickness of specimen after conditioning at $\varphi = 65 \%$ (80 %).

Wood density at given moisture content was derived from the ratio of the specimen mass and volume (STN 490108). The specimen moisture content before pressing, after pressing and after repeated acclimation was determined gravimetrically according to the Standard STN 490103.

RESULTS AND DISCUSSION

The average moisture content of the test specimens before the pressing was 17 % (Table 1). This moisture content was decided based on the results of our former experiments. The acclimated specimens were pressed under conditions described in the methodology. Mechanical, moisture and heat loading acting in interactions in the pressing process caused instant as well as

permanent changes in wood structure, which means also changes in wood properties. The immediate changes in wood properties directly influenced the wood compression during pressing process. The permanent modifications in wood structure and properties had impacts on its dimensional stability.

The moisture content of the test specimens after the pressing ranged from 13 to 1 % (Table 1). This decrease was participated by all the tested pressing parameters. The final moisture content during pressing depended on the pressing temperature and time. The moisture content was found markedly decreasing with raising temperature. There was also confirmed another decreasing trend in wood moisture content with prolonging pressing time. In all cases, the average moisture content under 40% compression was lower than the average moisture content under 20 % compression under the same conditions – due to the fact that the cross-sections of the specimens compressed by 40% were heated more then cross-sections of specimens compressed by 20 %.

Tab. 1 Moisture contents in specimens in individual phases of experiment (n =10).

Pressing time [min]	Statistical characteristics of moisture content	Temperature [°C]							
		160	180	200	220	160	180	200	220
		Comprimation by 20 %				Comprimation by 40 %			
		Conditioning before pressing ($\phi = 80 \%$, $t = 20 \text{ }^\circ\text{C}$)							
	\bar{x} [%]	17				17.02			
	s [%]	0.16				0.15			
After pressing									
2	\bar{x} [%]	13.08	12.12	10.30	8.09	10.68	9.85	6.92	5.16
	s [%]	0.57	0.55	0.45	0.60	0.68	1.00	0.70	0.57
4	\bar{x} [%]	11.28	10.58	6.88	4.37	7.33	6.69	3.25	1.55
	s [%]	0.70	0.45	0.59	0.51	0.64	0.76	0.56	0.42
6	\bar{x} [%]	10.25	8.40	4.07	–	5.08	3.36	1.07	–
	s [%]	0.37	0.27	0.55	–	0.95	0.69	0.48	–
I. conditioning after pressing ($\phi = 65 \%$, $t = 20 \text{ }^\circ\text{C}$)									
2	\bar{x} [%]	11.81	11.51	10.98	10.54	11.08	10.25	9.69	8.94
	s [%]	0.22	0.21	0.18	1.13	0.52	0.53	0.23	0.30
4	\bar{x} [%]	11.29	11.10	10.16	9.29	9.94	9.52	8.75	8.22
	s [%]	0.30	0.19	0.23	0.18	0.20	0.44	0.19	0.26
6	\bar{x} [%]	11.10	10.54	9.37	–	9.20	8.40	8.41	–
	s [%]	0.16	0.17	0.23	–	0.16	0.16	0.16	–
II. conditioning after pressing ($\phi = 80 \%$, $t = 20 \text{ }^\circ\text{C}$)									
2	\bar{x} [%]	17.35	17.26	17.08	16.79	16.71	16.32	16.25	15.72
	s [%]	0.34	0.28	0.18	0.27	0.51	0.48	0.22	0.35
4	\bar{x} [%]	17.22	17.18	16.93	16.47	16.34	15.84	15.95	15.38
	s [%]	0.37	0.23	0.26	0.24	0.42	0.33	0.33	0.38
6	\bar{x} [%]	17.12	16.98	16.63	–	15.85	15.35	15.85	–
	s [%]	0.23	0.37	0.18	–	0.53	0.56	0.37	–

After removing from the pressing equipment, the springback of each specimen was determined according to the Eq. (1). We also monitored the changes in specimen thickness after conditioning at $\phi = 65 \%$, and $\phi = 85 \%$ (Fig. 2). These changes in specimen thickness are related to the initial specimen thickness H_0 , making 16 mm at 20 % compression and 12 mm under 40 % compression.

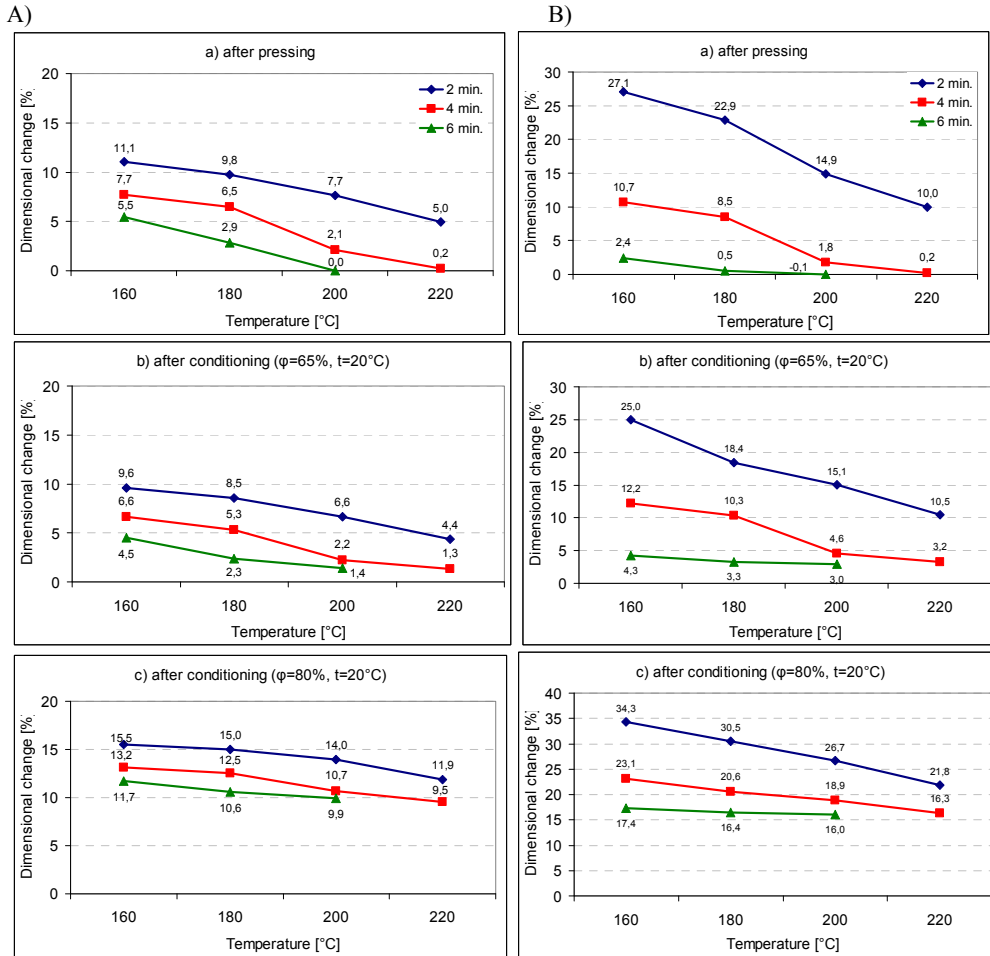


Fig. 2 Dimensional change dependent on pressing temperature and time. A) compression by 20 %, B) compression by 40 %.

The dimensional stability of specimens removed from the pressing equipment inversely correlated with varying moisture content. For both compression degrees, the lowest dimensional stability corresponded to the pressing temperature of 160 °C and the pressing time of 2 min. This fact is explained in Fig. 3 – showing that the temperature in the centre of specimens compressed by 20 %, heated for 2 min was ca 50 °C, which was not enough for ensuring their dimensional stability. The moisture concentrated in the centre of the compressed specimens caused a considerable springback. With raising temperature and increasing pressing time, the temperature in the specimen's centre increased and the moisture content decreased, improving, in such a way, the dimensional stability also inside the specimen. At a temperature of 220 °C and after 4 min pressing, the springback reached zero. In this case, the temperature in the specimens' centres ranged 100–110 °C (Fig. 3b). The same results were obtained after 6 min heating at 200 °C.

Having considered also other wood properties such as surface colour, the optimum pressing parameters seem: 200 °C for pressing temperature and 6 min for pressing time. The temperature of 220 °C is associated with the risk of noticeable degradation of wood surface layers due to the heat.

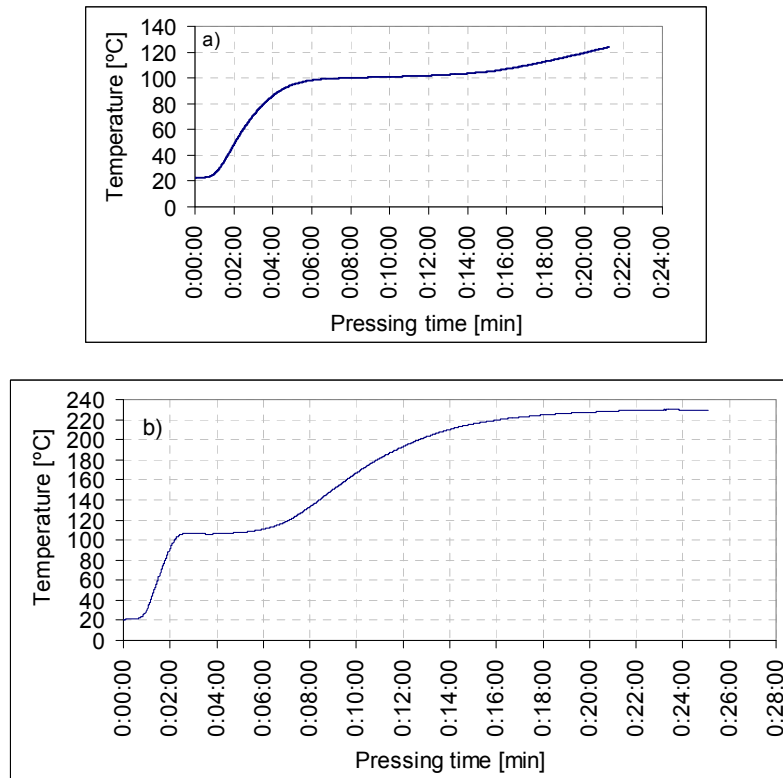


Fig. 3 Temperature change in the specimen's centre during pressing; a) pressing temperature 160 °C, b) pressing temperature 220 °C.

The compressed specimens were conditioned at temperature $t = 20\text{ °C}$ and air humidity $\varphi = 65\%$, associated with the wood equilibrium moisture content of 12 %. After the conditioning, the specimens compressed by 20 % exhibited average moisture contents ranging within 12.0–9.3 % (Table 1). The results show that the raised temperature and prolonged pressing time caused only very small changes in the wood sorption. A more distinct drop in wood sorption was recorded in specimens compressed by 40 %. In this case, the equilibrium moisture content was 11–8 %. The conditioning at $\varphi = 65\%$ caused well recognisable dimensional changes, correlating with varying moisture content (Fig. 2b). Further conditioning at $\varphi = 80\%$ caused significant increases in the specimens' moisture content values, in many cases reaching the equilibrium of 17 %. Despite this evidence, the specimens exhibiting these moisture content values had not restored their original dimensions (Fig. 2c). In this case, the best results were obtained for the pressing temperature of 200 °C and the pressing time of 6 min, or for 220 °C and 4 min, but not even these values were sufficient for guaranteeing the dimensional stability of the compressed wood in environment with high relative air humidity.

The causal factors for springback after the load removal are elastic strains (instant and time-elastic) and restoration of hydrogen bonds. The renewed hydrogen bonds enable reorganisation of macromolecular and submicroscopic structures and conformations. The result is renewal of hygroscopic deformation of wood – wood “swelling”. These changes are getting more pronounced with amounts of water remaining in the compressed wood.

The results show that these deformations depend on temperature. The molecular mechanisms underlying changes in wood associated with temperature is different from the

changes associated with moisture. Wood heating accelerates the movements of its basic elements (thermal movements), with inducing significant physical and chemical changes in this material (KAČÍKOVÁ and KAČÍK 2011).

Wood polymers are most frequently characterised with three temperature ranges and the three corresponding states – glassy state, viscoelastic (transitory) state and viscous flow (rubbery state) (KÚDELA 1992). For some polymers, IRVINE (1984) reports even five possible temperature ranges. Five temperature ranges are also observable in lignins of some broadleaved woody plants (KUBO *et al.* 1997). The different ranges are associated with different polymer properties and performance. From this viewpoint is important T_g temperature (glass transition).

In case of dry hemicelluloses and lignin, $T_g > 100^\circ\text{C}$ (IRVINE 1984, SOLÁR 1997, OLSON and SALMÉN 1997 and others). The last-cited works, however, are showing evidence for an especially significant dependence of T_g on moisture content. The temperature range for T_g is from 60 to 100°C for wet lignin, and from 0° to 100°C for hemicelluloses. The values vary with the moisture content. With increasing moisture content increases also the difference in T_g between the two discussed wood components. It is because the hemicelluloses in wood are highly hygroscopic and they absorb the considerable water amounts.

In this temperature range, no T_g values can be observed for cellulose – due to the high crystallinity of this component. WOODWARD (1980) reports for cellulose a glass transition T_g value of 230°C . Some authors cited in LINDSTRÖM *et al.* (1987) report 200°C for T_g of dry cellulose, with other T_g values being inversely dependent on moisture content.

The glass transition of wood in plasticization process is supposed controlled primarily by the T_g of lignin. In case of beech wood, the T_g range is 65 – 75°C (OLSSON and SALMÉN 1997). The last cited authors suggest that these low T_g values of beech wood were mainly due to high abundance of methoxyl groups in lignin. As it follows from KÚDELA (2005), T_g temperature can be controlled, to some extent, also by the duration of thermal or hydrothermal treatment.

Reduction of wood hydrophilicity and permanent dimensional stabilisation of wood after pressing requires reaching the rubbery state. For reaching the rubbery state of lignin in pressing wood with low moisture content, there are necessary substantially higher heating temperatures (180 – 200°C) – documented with the results of ITO *et al.* (1998b), INOUE *et al.* 1998 and DWIANTA *et al.* 1999.

Considering our initial moisture content of 17% (air-dried wood) and considering the fact that wood moisture content exhibits significant decrease during pressing, we decided for the pressing temperatures from 160 to 220°C . These values should guarantee the third transition phase – rubbery state for wood polymers during wood pressing. This is true, however, only under the assumption that the body has been heated across the entire cross-section. This assumption, however, was not met within our pressing times.

Our results allow us, in relation to permanent changes, to declare 200 – 220°C as the optimum pressing temperature range and 4 – 6 min as the optimum pressing time range for specimens thick 20 mm. With these parameters, there was obtained almost 100% dimensional stability after pressing. However, the same did not hold under moisture loading. Increasing moisture load caused decreasing stability of the test specimens.

The obtained results indicate that, during pressing, lignin turned to rubbery state and served, in our opinion, an important role for specimens' dimensional stability. The central wood layers, however, did not reach this state, which we suppose to be the primary cause of worsening the dimensional stability of specimens after moisture loading. The results suggest that there is necessary to decide the pressing time guaranteeing appropriate heating also for central layers. This time will depend on the pressing temperature and on the pressed body thickness. Similar results were also obtained by ITO *et al.* (1998a), investigating the mechanism of permanent fixation of pressed wood. The authors observed that higher pressing temperature might need shorter pressing time. The dimensional stabilisation at pressing temperature of 200°C required pressing time of 4 min, while at 180°C , the pressing time was needed three times more.

The pressing parameters also influence the pressed wood density. Table 2 shows that the average density of beech wood after pressing was from 765 to 1040 kg·m⁻³. BLOMBERG *et al.* (2006) report the average density values for seven wood species pressed under a constant pressure of 130 MPa, ranging within 750–1100 kg·m⁻³.

Tab. 2 Density in specimens in individual phases of experiment (n =10).

Pressing time [min]	Statistical characteristics of density	Temperature [°C]							
		160	180	200	220	160	180	200	220
		Comprimation by 20 %				Comprimation by 40 %			
After pressing									
2	\bar{x} [kg·m ⁻³]	765	762	775	779	874	881	930	957
	s [kg·m ⁻³]	21,0	20,9	20,6	21,3	36,8	57,6	29,6	32,6
4	\bar{x} [kg·m ⁻³]	772	801	795	794	947	961	1018	1011
	s [kg·m ⁻³]	20,7	74,1	21,5	17,5	40,8	58,2	28,6	37,4
6	\bar{x} [kg·m ⁻³]	788	796	795	–	1003	1038	1009	–
	s [kg·m ⁻³]	14,6	18,6	21,6	–	37,6	50,6	30,2	–
I. conditioning after pressing ($\varphi = 65 \%$, $t = 20 \text{ }^\circ\text{C}$)									
2	\bar{x} [kg·m ⁻³]	761	764	785	802	895	954	961	1025
	s [kg·m ⁻³]	27,4	17,5	20,5	12,8	64,3	76,3	26,6	31,2
4	\bar{x} [kg·m ⁻³]	778	792	814	808	981	1013	1041	1030
	s [kg·m ⁻³]	24,7	10,8	27,3	22,1	38,8	56,6	33,7	32,7
6	\bar{x} [kg·m ⁻³]	811	811	817	–	1046	1049	1026	–
	s [kg·m ⁻³]	9,5	12,2	33,2	–	47,5	48,1	30,8	–
II. conditioning after pressing ($\varphi = 80 \%$, $t = 20 \text{ }^\circ\text{C}$)									
2	\bar{x} [kg·m ⁻³]	760	757	771	780	865	870	899	930
	s [kg·m ⁻³]	21,5	19,1	20,9	21,3	46	55,5	28,4	33,4
4	\bar{x} [kg·m ⁻³]	771	776	791	794	911	926	956	965
	s [kg·m ⁻³]	22,3	14,4	20,4	20,4	43,2	64,0	29,2	39,9
6	\bar{x} [kg·m ⁻³]	784	790	793	–	947	988	952	–
	s [kg·m ⁻³]	17,5	18,1	19,4	–	45,0	55,1	32,1	–

The results of the last cited authors demonstrate that the pressed wood density is primarily affected by the compression degree and by wood species. Our results have also confirmed an important influence of dimensional stability. At the same compression degree, higher density was obtained in specimens with better stabilised dimensions. In Fig. 2 we can see that the dimensional stability improved with increasing pressing temperature and pressing time. This means that the final density values were also controlled by these parameters.

The final density of the pressed wood is important from the viewpoint of its mechanical performance. Wood mechanical properties increase linearly with increasing wood density, equally in untreated and pressed wood (BLOMBERG 2006, KÚDELA 2010).

The concern was about wood density at specified moisture contents when the wood density was also partly influenced by the wood moisture. The specimens did not exhibit distinct changes in density after conditioning at $\varphi = 65 \%$. Statistically significant differences identified in some cases were not significant from the viewpoint of practice. Conditioning the specimens at $\varphi = 80 \%$ resulted in a decreasing trend in wood density, despite the moisture content values were higher in all cases. The underlying cause is that the increase in wood volume due to increasing wood moisture content was more rapid than the corresponding increase in the wood mass.

The results suggest that the crosscut density patterns in pressed wood (density patterns in the pressing direction) will not be homogeneous. The variable density profiles reported in WANG

and COOPER (2005) show the same evidence. The consequence is lower dimensional stability of the pressed wood (KÚDELA and REŠETKA 2011).

CONCLUSIONS

The results of our experiments have confirmed the dependence of dimensional stability on pressing temperature and pressing time. The dimensional stability improved significantly with increasing pressing temperature and time.

Very good stability after pressing was obtained for pressing at the temperature of 200 °C for 6 min, or after pressing at 220 °C for 4 min. These pressing conditions also induced significant decrease in moisture content and in sorption capacity of the pressed wood.

The tested pressing parameters did not guarantee for the pressed specimens appropriate dimensional stability after moisture loading. The results revealed that the specimens were not sufficiently heated inside. It follows that prolongation of the pressing time is necessary.

LITERATÚRA

- BÄCHLE, F., NIEMZ, P., SCHNEIDER, T. 2007. Physical-mechanical properties of hard- and softwood heat treated in an Autoclave. In: European Conference on Wood Modification 2007: Processing. Bangor, UK, BC, pp. 177–182.
- BLOMBERG, J. 2006. Mechanical and Physical Properties of Semi-Isostatically Densified Wood. LTU Skellefteå: Luleå University of Technology, Division of Wood Science and Technology, 2006:28, 62 pp. ISSN I402-I544.
- BLOMBERG, J., PERSSON, B., BEXELL, U. 2006. Effects of semi-isostatic densification on anatomy and cell shape recovery on soaking. *Holzforschung*, 60: 322–331.
- CLAIR, B., ARINERO, R., LÉVÊQUE, G., RAMONDA, M., THIBAUT, B. 2003. Imaging the mechanical properties of wood cell wall layers by atomic force modulation microscopy. *IAWA Journal*, 24(3): 223–230.
- DWIANTO, W., MOROOKA, T., NORIMOTO, M., KITAJIMA, T. 1999. Stress relaxation of sugi (*Cryptomeria japonica*, D. Don) wood in radial compression under high temperature steam. *Holzforschung*, 53: 541–546.
- ESTEVEZ, B. M., PEREIRA, H. M. 2009. Wood modification by heat treatment. In *BioResources*, 4(3): 370–404.
- HIGASHIHARA, T., MOROOKA, T., NORIMOTO, M. 2000. Permanent fixation of transversally compressed wood by steaming and its mechanism. *J. Jap. Wood Res. Soc.*, 46(4): 291–297.
- CHUCHRIANSKIJ, P. N. 1953. *Lisovanie dreva*. Bratislava: Práca, 156 pp.
- INOUE, M., KODAMA, J., YAMAMOTO, Y., NORIMOTO, M. 1998. Dimensional stabilization of compressed wood using high-frequency heating. *J. Jap. Wood Res. Soc.*, 44(6): 410–416.
- IRVINE, G. M. 1984. The significance of the glass transition of lignin and hemicelluloses and their measurement by differential thermal analysis. *Tappi J.*, 67(5): 118–121.
- ITO, Y., TANAHASHI, M., SHIGEMATSU, M., SHINODA, Y., OHTA, CH. 1998a. Compressive-moulding of wood high-pressure steam-treatment. Part 1. Development of compressively moulded squares from thinnings. *Holzforschung*, 52(2): 211–216.
- ITO, Y., TANAHASHI, M., SHIGEMATSU, M., SHINODA, Y. 1998B. Compressive-moulding of wood high-pressure steam-treatment. Part 2. Mechanism of permanent fixation. *Holzforschung*, 52(2): 217–221.
- JOHANSSON, D., PERSSON, M., MORÉN, T. 2006. Effect of heat treatment on capillary water absorption of heat-treated pine, spruce and birch. In *Wood Structure and Properties '06* (Eds. Kurjatko *et al.*), Zvolen: Arbora Publishers, pp. 251–255. ISBN 80-968869-4-3.
- KAČÍKOVÁ, D., KAČÍK, F. 2011. *Chemické a mechanické zmeny dreva pri termickej úprave*. Zvolen: TU vo Zvolene, 71 pp.
- KÖZSEGI, L., ZEMIAR, J., ŠTEFEK, P. 2000. Rozmerová stabilita dreva tvárneného lisovaním a plastifikovaného mikrovlnným ohrevom. *Acta Facultatis Xylogologiae Zvolen*, 42(1): 99–107.
- KUBO, S., ISHIKAWA, N., URAKI, Y., SANO, Y. 1997. Preparation of lignin fibers from softwood acetic acid lignin. Relationship between fusibility and the chemical structure of lignin. *Mokuzai Gakkaishi*, 43(8): 655–662.

- KÚDELA, J. 1990. Vplyv vlhkosti a teploty na mechanické vlastnosti bukového dreva. [Dizertačná práca.] Zvolen DF Technickej univerzity. 150 pp.
- KÚDELA, J. 1992. Štúdium vplyvu teploty na vlastnosti dreva. In: Wood burning '92. Zvolen: Technická univerzita vo Zvolene, pp. 201–222.
- KÚDELA, J. 2005. Vlhkostné a tepelné namáhanie bukového dreva. Zvolen: Technická univerzita vo Zvolene, 141 pp. ISBN 80-228-1486-5.
- KÚDELA, J. 2010. Mechanické vlastnosti dreva. In Parametre kvality dreva určujúce jeho finálne použitie. Zvolen: Technická univerzita vo Zvolene, pp. 101–127. ISBN 978-80-228-2095-0.
- KÚDELA, J., REŠETKA, M. 2011: Influence of high pressing temperature on dimensional stability of beech wood. Ann. WULS – SGGW, For. and Wood Technol., 75: 19–25.
- LINDSTRÖM, T., TOLONEN, J., KOLSETH, P. 1987. Swelling and mechanical properties of cellulose hydrogels. Part VI. Dynamic mechanical properties. *Holzforschung*, 41(4): 225–230.
- NAVI, P., GIRARDET, F. 2000. Effect of thermo-hydro-mechanical treatment on the structure and properties of wood. *Holzforschung*. 54(3): 287–293.
- OLSON, A. M., SALMÉN, L. 1997. Humidity and temperature affecting hemicellulose softening of wood. In *Mechanical Performance of Wood and Wood Products. Wood Water Relations. International Conference of Copenhagen: COST Action E8*, pp. 267–279.
- PERELYGIN, L. M. 1965. *Náuka o dreve*. 2. vydanie. Bratislava: Alfa, 1965. 448 pp.
- REINPRECHT, L., VIDHOLDOVÁ, Z. 2011: *Termodrevo*. OSTRAVA: ŠMÍRA-PRINT, s.r.o., 89 pp.
- SEBORG, R. M., MILLETT, M. A., STAMM, A. J. 1962. Heat-stabilized compressed wood. FPL, Report No. 1580, p. 22.
- SOLÁR, R. 1997: *Zmeny lignínu v procesoch hydrotermickej úpravy*. 1. vyd. Zvolen: Technická univerzita vo Zvolene, 57 pp.
- STAMM, A. J., SEBORG, R. M. 1941. Resin treated, laminated, compressed wood. *Trans. Am. Inst. Chem. Eng.*, 37: 385–397.
- WANG, J. Y., COOPER, P. A. 2005. Effect of grain orientation and surface wetting on vertical density profiles of thermally compressed fir and spruce. *Holz Roh- u. Werkstoff*, 63: 397–402.
- WOODWARD, C. 1980: Fractured surfaces as indicators of cell wall behavior at elevated temperatures. *Wood Sci.*, 13(2): 83–96.

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