

Shrinkage and Stability of Thermo-Mechanically Modified Aspen Wood

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This work presents dimensional and shape changes of aspen wood due to surface embossing. The influences of wood treatment, degree of pressing, and initial moisture content on the stability of wood were investigated. The stability of the wood was investigated through dimensional changes (volumetric and linear shrinkage) and shape changes (permanent deformations). The aspen wood was treated by steaming and radio frequency (RF) heating. The treatment did not have a significant effect on the moisture and shape stability of wood after pressing. The non-treated wood showed better stability after pressing.

Keywords: Pressing; Shape stability; Volumetric shrinkage; Linear shrinkage; Aspen; Plastic deformations; Moisture; Moisture content

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INTRODUCTION

Surface embossing is a method of improving wood's surface appearance and creating decorative properties, in which the wood surface is formed using profile plates. In the case of smoothed plated pressing, the density and hardness of the wood surface increases.

For pressing, press machines are used with heated profiled plates. In general the desired surface shaping is achieved by the effects of heat and pressure on untreated or treated (by plasticizing) wood, which is stabilized in the allotted time. In case of continuous pressing (by rolling), phase of stabilization under pressure is not necessary and maintaining the new shape depends on wood stability (Gáborík and Žitný 2007; Gaff and Zemiar 2008).

This research was aimed at the industrial utilization of soft deciduous trees. Aspen wood (*Populus tremula* L.) falls under this category. It has an inexpressive wood structure, so it is possible to improve its decorative appearance by embossing it (Zemiar and Gaff 2005).

The focus of this work is stability of pressed aspen wood, which was evaluated through dimensional changes (volumetric and linear shrinkage) and shape changes (plastic (permanent) deformations). Linear shrinkage was obtained in the pressing direction, *i.e.*, perpendicular to the wood grain in the tangential direction. Stability was investigated on untreated wood and on wood treated by steam plasticizing and radio frequency (RF) heating at four initial moisture contents and pressed at five different degrees of pressing (Zemiar *et al.* 2005; Jakúbková 2003).

MATERIALS AND METHODS

Sample Preparation

The experimental aspen trees (*Populus tremula* L.) were 60 years old and grew in the Javorie mountains area in central Slovakia, southeast from Zvolen city. The zones suitable for samples were cut from the trunk at a height of 1.5 m from the stump. The zones, which were in middle distance between the pith and bark, were chosen for sample preparation. From these parts were cut 50 cm long sections which contained 25 mm wide annual rings. For experiments, clear aspen samples with dimensions of 50 × 50 × 50 mm were used. All the samples were air-conditioned in the conditioning room for more than five months before moisture conditioning.

Basic Preparation

All of the air-conditioned samples were divided into two groups in relation to treatment – untreated samples (non-plasticized and non-compressed) and treated (plasticized and compressed) samples. Untreated samples served as a reference standard. For each combination (initial moisture content × treatment), 20 samples were used, so that the entire research contained 520 samples. Furthermore, all samples were divided into four groups according to initial moisture content, namely 8, 16, 30, and 100%. The samples with initial moisture content less or equal than the fiber saturation point - FSP (8, 16, and 30%) were conditioned in a conditioning chamber by achieving of equilibrium moisture content (EMC). The conditioning chamber provided different conditions in relation to relative humidity of air and temperature (Table 1). The EMC above FSP (100%) were achieved by water soaking. The actual EMC of each sample was measured by weighing method after conditioning. Table 1 shows the average values of equilibrium moisture contents for individual group.

Table 1. Moisture Contents and Conditioning Conditions of Samples

Required initial moisture content (%)	Average values of EMC after conditioning (%)	Scattering of EMC values after conditioning (%)	Conditions during conditioning	
			Relative humidity of air (%)	Temperature (%)
8	8.4	7.9 – 8.89	43	20
16	16.3	15.75 – 16.85	78	
30	31.2	29.3 – 33.1	97	
100	98.8	97.4 – 100.2	water soaking	20

Treatments

Treatment was carried out in two basic ways: plasticizing and compression. **Plasticizing** was achieved by steaming and RF (radio-frequency) heating. **Steaming** was carried out in a steaming device (device has been designed by us), which contained water at the bottom. Before testing, the water was heated to the boiling point, and then the samples were inserted into the steaming device. Samples were placed on a metal grate over the water. During heating, the temperature in the device was kept at about 95°C. Plasticizing of samples took 20 min. **RF heating** was carried out so that the wood was placed between two electrodes that are connected to the source of a 300 kHz frequency electrical power supply. The heating time of samples was 6 min.

Compression was carried out perpendicularly to the wood grain in the tangential direction by 5 degrees of pressing, namely 10, 20, 30, 40, and 50% of the original sample thickness. Longitudinal direction (length) of wood samples was parallel (horizontal) with plates and perpendicular to compression direction. Samples were placed on the preheated (95°C) compression plate and pressed to the required degree of pressing.

Measurement

Shrinkage was carried out 4 times - before heating, just after compressing, after conditioning at 12% moisture content, and also after drying to oven-dry state. Dimensions necessary for the calculation of shrinkage were those that have been measured after plastic deformation (after conditioning at 12% moisture content). Every dimension necessary for the calculation of shrinkage was measured at 3 different places, but for the calculation only the average value of them was used.

Measurement of thickness required for the calculation of deformation was carried out at 5 places of each sample (4 corners and 1 center of sample). The average values of these data were used for the calculation of the engineering normal strain.

All dimensions and dimensional changes were measured with a precision 0.1 mm using the digital caliper from Mitutoyo company.

Evaluation and Calculation

Results evaluation was based on comparison values, which had to be converted to 12% moisture content.

Treated samples were conditioned at 12% moisture content after compression. Conditioning was carried out according to ISO 3129 (2012) using the conditions for 12% equilibrium moisture content (EMC), namely $\phi=65\pm3\%$ and $t=20\pm2^\circ\text{C}$. For comparison, the shrinkage results of untreated (non-compressed and non-plasticized) samples were converted to 12% moisture content by using Equation 1, which was introduced by Požgaj *et al.* (1997) and Glass and Zelinka (2010),

$$\alpha_t(w) = \alpha_t \left(1 - \frac{w}{FSP} \right) \quad (1)$$

where $\alpha_t(w)$ is the shrinkage corresponding to certain moisture content [%], α_t is the total shrinkage from fiber saturation point (FSP) to oven-dry [%], and w is the moisture below FSP, for which the shrinkage is calculated [%].

Shrinkage calculated according to Equation 1 was subtracted from the total shrinkage represented by Equation 2, whereby the obtained value was comparable with the shrinkage of plasticized samples conditioned to 12% moisture content (shrinkage from 12% moisture content to oven-dry state). Oven-dry state is the attainment of constant state generally after drying in an oven set at $103 \pm 2^\circ\text{C}$ for 24 h as mentioned by Walker *et al.* (1993).

Total shrinkage in tangential direction was calculated according to the Equation 2 from ISO 4469 (1981),

$$\alpha_t = \frac{b_{tw} - b_{t0}}{b_{tw}} * 100 \quad (2)$$

where α_t is the total shrinkage of sample in tangential direction [%], b_{tw} is dimension of test sample in tangential direction at certain moisture w [m], and b_{t0} is dimension of oven-dry test sample in tangential direction [m].

Total volumetric shrinkage was calculated according to the Equation 3 from ISO 4858 (1982),

$$\alpha_v = \frac{V_w - V_0}{V_w} * 100 \quad (3)$$

where α_v is the volumetric shrinkage of sample [%], V_w is the volume of test sample at certain moisture w [m³], and V_0 is the volume of the oven-dry test sample [m³].

Shape stability was evaluated by plastic deformations, which were determined immediately after opening the pressing machine and conditioning of samples at 12% moisture content (Fig. 1). Plastic deformations were represented by an engineering normal strain (in percent) which was calculated according to Equation 4,

$$\varepsilon = \frac{h_{12} - h_0}{h_0} * 100 \quad (4)$$

where ε is the engineering normal strain [%], h_0 is the original dimension (thickness) of the sample in pressing direction [m], and h_{12} is the final dimension (thickness) of the sample in pressing direction after conditioning to 12% moisture content [m].

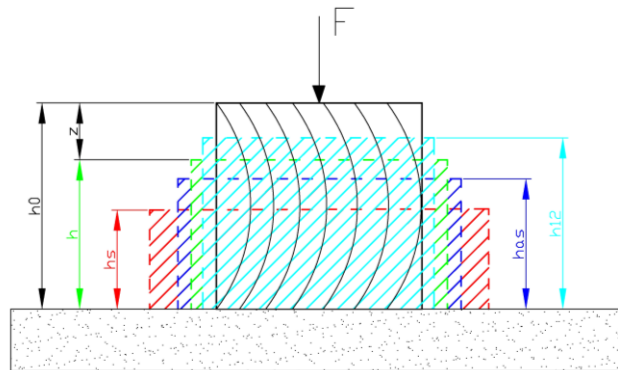


Fig. 1. Representation of the behavior of the sample during compression and after conditioning

Note: h_0 – the original thickness of the sample, h – thickness of sample after releasing of compression machine (elastic deformations), z – „the residual“ deformations (elastic recovery + plastic deformations), h_s – thickness of sample after compression, h_{as} – thickness of sample in oven-dry state, h_{12} – the final thickness of the sample in pressing direction after conditioning to 12% moisture content.

Compression of wood also changes its density, which was determined as an auxiliary indicator. Density was calculated according to the Equation 5 from ISO 3131 (1975),

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \quad (5)$$

where ρ_w is the density of the test sample at certain moisture content w [kg/m^3], m_w is the mass (weight) of the test sample at certain moisture w [kg], a_w , b_w , l_w are dimensions of the test sample at certain moisture w [m], and V_w is the volume of the test sample at certain moisture w [m^3].

The density of wood after treatment was also calculated according to the Equation 6 from ISO 3131 (1975),

$$\rho_{pl} = \frac{m_{pl}}{a_{pl} * b_{pl} * l_{pl}} = \frac{m_{pl}}{V_{pl}} \quad (6)$$

where ρ_{pl} is the density of the test sample after treatment [kg/m^3], m_{pl} is the mass (weight) of the test sample after treatment [kg], a_{pl} , b_{pl} , l_{pl} are dimensions of the test sample after treatment [m], and V_{pl} is the volume of the test sample after treatment [m^3].

During the experiments it was necessary to determine and verify a moisture content of samples before or after treatments. These calculations were carried out according to ISO 3130 (1975) and Equation 7,

$$w = \frac{m_w - m_0}{m_0} * 100 \quad (7)$$

where w is the moisture content of the samples [%], m_w is the mass (weight) of the test sample at certain moisture w [kg], and m_0 is the mass (weight) of the oven-dry test sample [kg].

Drying to oven-dry state was also carried out according to ISO 3130 (1975) using the following procedure: The samples are placed in the drying oven at a temperature of $103 \pm 2^\circ\text{C}$ until constant mass has been reached. Constant mass is considered to be reached if the loss between two successive weighing carried out at an interval of 6 h is equal to or less than 0.5% of the mass of the test sample. After cooling the test samples to approximately room temperature in a desiccator, the sample was weighed rapidly enough to avoid an increase in moisture content by more than 0.1%. The accuracy at weighing shall be at least 0.5% of the mass of the test sample.

RESULTS AND DISCUSSION

One of the side effects of embossing is wood densification. Wood densification depends on wood species, compression, treatment, moisture, and other factors. With increasing degree of pressing and decreasing initial moisture content, the density of untreated and treated pressed wood increases. The highest increase of values, approximately 35%, was determined at aspen wood treated by RF heating with initial moisture content of 8% and at 50% degree of pressing. The same values were determined at untreated and pressed wood, where increase of value reached 25%. Gáborík and Dudas (2006) obtained similar results.

From the perspective of the impact of wood treatment, the increase of density tends to grow from untreated through treated wood by steaming to RF heating. The density of the untreated aspen wood was in range of $\rho_w = 354$ to $502 \text{ kg}/\text{m}^3$. Plasticizing

and compression increased the density in range of $\rho_{pl} = 420$ to 543 kg/m^3 . Plasticizing did not have a significant influence on changes in density. This fact was also introduced by Gáborík *et al.* (2003) and Gaff (2003).

The stability of aspen wood was evaluated by shape and dimensional changes. Wood is considered stable if its volumetric and dimensional changes are not significantly influenced by moisture. The results confirmed that wood compression does not have a significant influence on aspen wood shrinkage (Majchráková 1999). Shrinkage of non-plasticized and pressed aspen wood was increased by an average of 0.16% (Table 2, Fig. 2 and 3). The combination of compression and plasticizing had a greater impact on shrinkage. Plasticizing releases internal stresses and pressing can destruct wood's microstructure, which is the reason for an increase of wood shrinkage values. In this case, shrinkage was increased two-fold, compared to non-plasticized wood. The higher values were only obtained from wood plasticized by RF. Volumetric shrinkage of plasticized wood (from moisture content 12% to oven-dry state) was in range $\alpha_V = 6.05$ to 10.16% , and linear shrinkage in tangential direction was $\alpha_t = 3.71$ to 6.41% . Steamed wood had values of shrinkage in range $\alpha_V = 6.80$ to 8.36% and $\alpha_t = 3.70$ to 5.28% . These values were lower, but the scattering of the values were considerably lower.

The value of total volumetric shrinkage of untreated aspen wood was 12.58% and total linear shrinkage in tangential direction was 7.82% . After recalculating (shrinkage from moisture content 12% to oven-dry state), the values were $\alpha_V = 4.72\%$ and $\alpha_t = 2.93\%$ (Table 2, Fig. 2, and Fig. 3). Similar shrinkage results were introduced by Sergovskij (1975), while Metsälä (2012) reached the same values as we did. Metsälä states the following values of shrinkage, $\alpha_V = 4.4$ to 5.12% and $\alpha_t = 2.68$ to 3.4% (the values for untreated wood and after conversion from 12% moisture content to oven-dry state). In our case the initial moisture content had the most influence on plasticized wood because the highest shrinkage values were at 16% moisture content.

Table 2. Aspen Wood Shrinkage

Initial moisture content (%)	Volumetric shrinkage (%)			
	RF heated and compressed*	Steamed and compressed*	Non-plasticized and compressed*	Non-plasticized** and non-compressed
8	7.43	7.27	5.89	4.72
16	10.16	8.36	3.73	
30	6.38	7.29	4.30	
100	6.05	6.80	5.60	
Average	7.51	7.43	4.88	
	Linear shrinkage (%)			
8	5.18	4.87	4.0	2.93
16	6.41	5.28	2.49	
30	4.03	4.32	2.80	
100	3.71	3.70	3.69	
Average	4.83	4.54	3.24	

Notes: *Average values of results from measured shrinkage values from 12% moisture content to oven-dry state.

**Results from recalculated shrinkage values from 12% moisture content to oven-dry state in compliance with Equation 1

After taking material out of the pressure machine, elastic deformations appears immediately and later plastic deformations, which cause shape instability. In order to eliminate the impact of elastic deformation and varying moisture on the results, the material was conditioned to 12% moisture content and then investigated the plastic deformations.

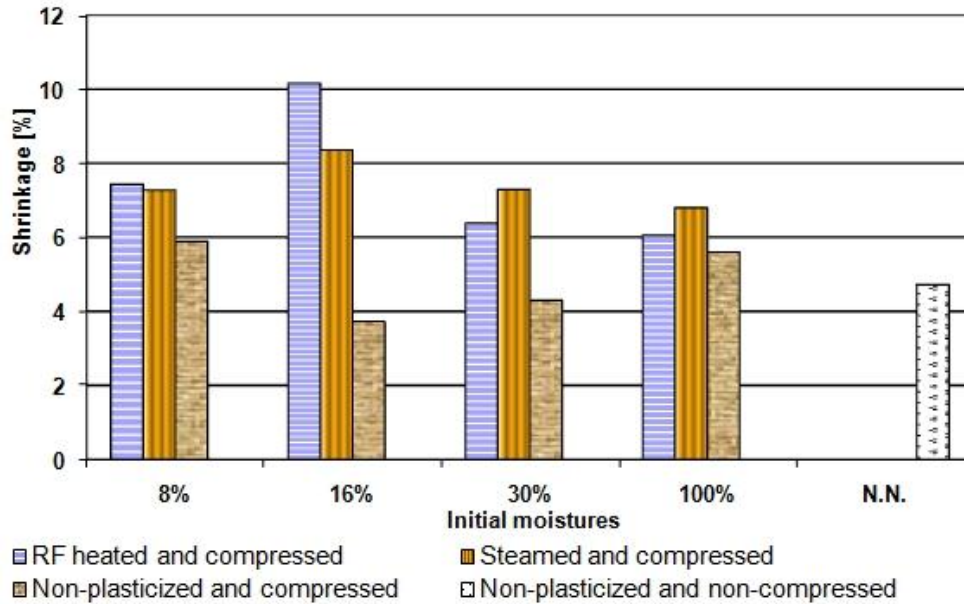


Fig. 2. Volumetric shrinkage of aspen wood from 12% moisture content to oven-dry state

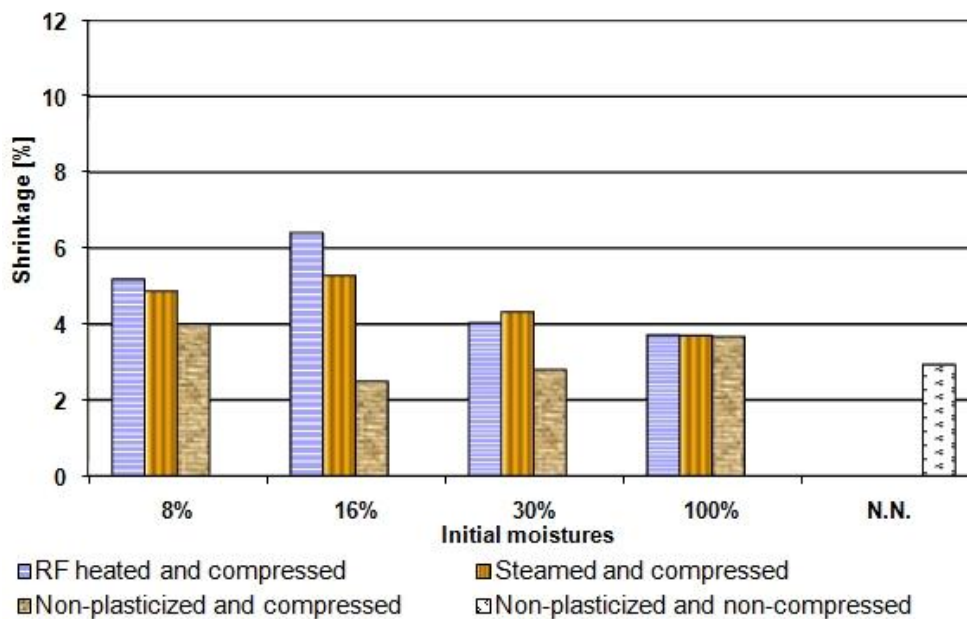


Fig. 3. Linear shrinkage of aspen wood from moisture 12% to oven-dry state

Note: **N.N.** (Non-plasticized and Non-compressed) – reference standard, i.e., shrinkage of untreated wood for specified moisture range

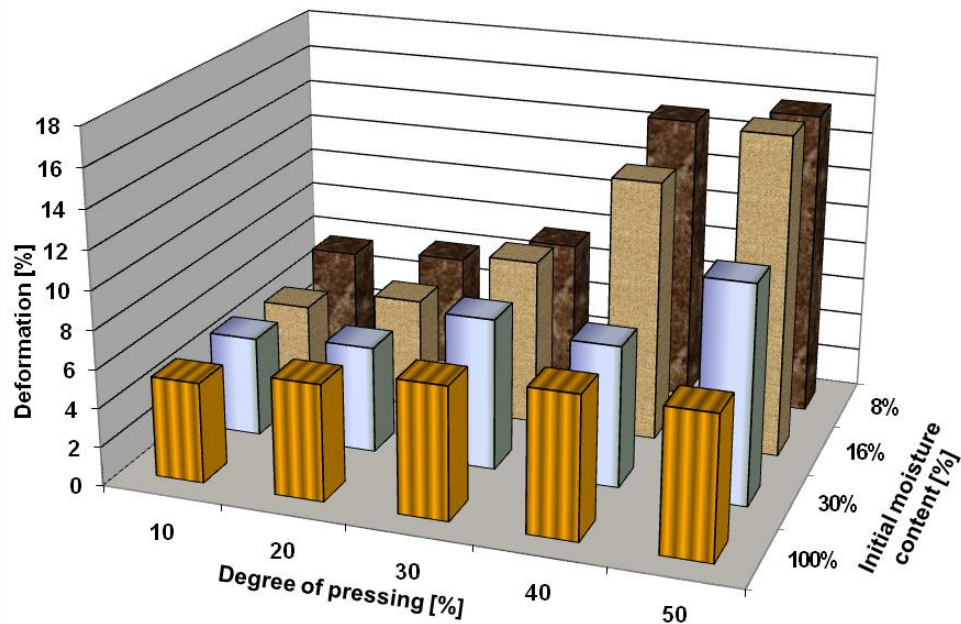


Fig. 4. Plastic deformation of non-plasticized aspen wood after conditioning to 12% moisture content

It can be asserted that plasticizing does not have a significant influence on shape stability. Using both methods, permanent deformations were almost identical and reached a value approximately 15% at 50% compression. Changes in permanent deformation were influenced more by initial moisture content and degree of pressing. In reducing the initial moisture content, the proportion of plastic deformation increases, which increases the dimensional stability of the material.

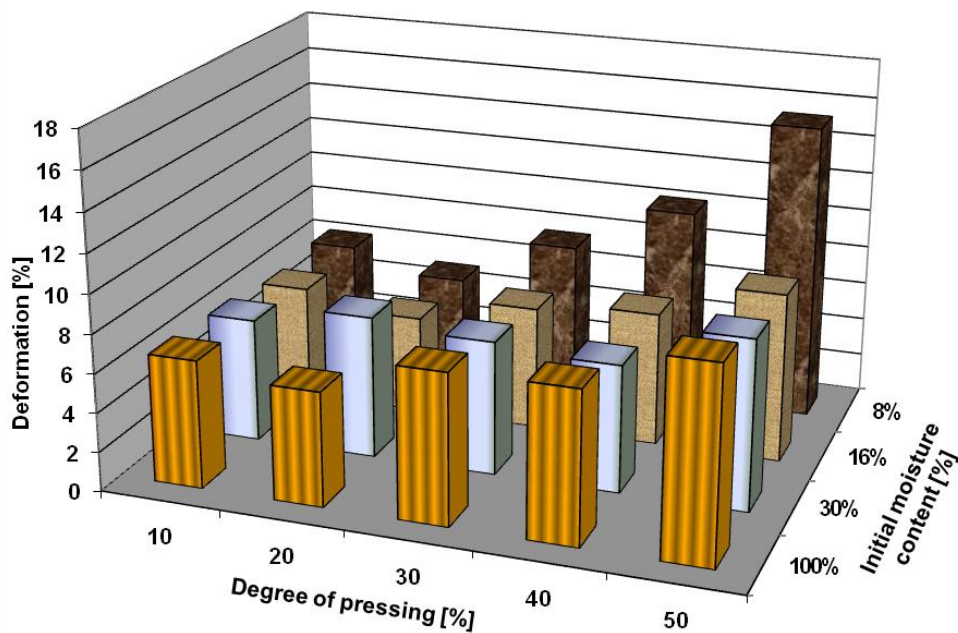


Fig. 5. Plastic deformation of aspen wood plasticized by steam and conditioned to 12% moisture content

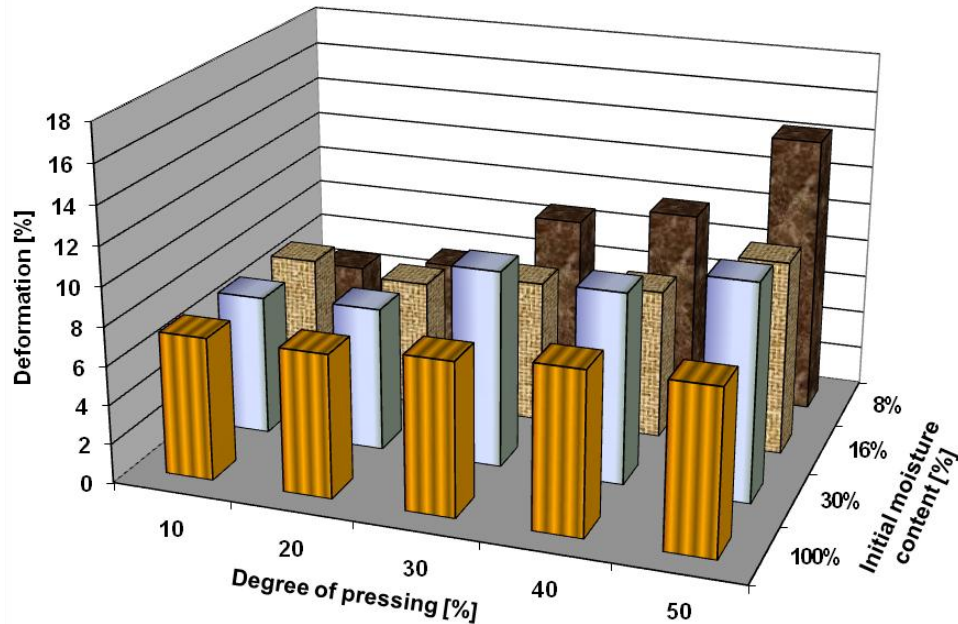


Fig. 6. Plastic deformations of aspen wood plasticized by RF heating and conditioned to 12% moisture content

At lower initial moisture contents (8% and 16%) and with an increasing degree of pressing, values of permanent deformation were higher (15%), as well as shape stability. At higher initial moisture contents (30% and 100%), the degree of pressing did not have a significant effect (Figs. 5 and 6).

This research improves the knowledge about the impact of compression and plasticizing on aspen wood. In the future, this work will also focus on characteristics of aspen wood, such as modulus of elasticity, modulus of rupture, and eventually others. After completion of all basic data, we can suggest specific uses for practice.

CONCLUSIONS

1. In this work, dimensional changes in aspen wood were evaluated by volumetric and linear shrinkage. These changes were negligible in non-plasticized and compressed wood. Plasticizing and compression of aspen wood doubled the shrinkage values in comparison with non-plasticized wood at 16% moisture content. Recalculated volumetric shrinkage (from 12% moisture content to oven-dry state) had values $\alpha_v = 6.05$ to 10.16%, and linear shrinkage was $\alpha_t = 2.49$ to 6.41%.
2. Untreated wood had values of $\alpha_v = 4.72\%$ and $\alpha_t = 2.93\%$. Untreated wood had a total volumetric shrinkage of 12.58% and a linear shrinkage in tangential direction of 7.82%. Influence of plasticizing methods did not show significant differences.
3. For dimensional stability evaluated by plastic deformations, some monitored factors showed more significantly than in dimensional changes. Reduction of initial moisture content and an increase in the degree of compression causes an increase in the value of plastic - permanent deformation, which is positively reflected in the increased stability of the wood. Maximal value of plastic deformation $\varepsilon = 15\%$ was reached at

8% initial moisture content and at 50% compression. Also in this case the shape stability plasticizing methods did not differ significantly among themselves.

4. Aspen wood with an initial moisture content of 16% and with maximal compression of 50% is suitable for embossing, compression, and other similar methods of enhancement.

ACKNOWLEDGMENTS

The authors are grateful for the support of VEGA grant No. 1/0422/12, “Modifying of the properties of wood for the purpose of the 3D forming.”

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Article submitted: October 30, 2012; Peer review completed: January 4, 2013; Revised version received and accepted: January 17, 2013; Published: January 18, 2013.