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MECHANICAL CHARACTERISATION OF ACCORDIONISATED WOOD, EFFECT OF RELAXATION CONDITIONS

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Abstract:
After longitudinal compression the natural wood will be bent easier. The relaxation after compression results in better properties. The maximum deflection increases with the relaxation time and with the decreasing of the modulus of elasticity (MoE), while the needed force for the same bending also decreases. The bending strength (MoR) changes intensively just with a long-time relaxation. The nanoindentation (NI) showed, that changes can be found also inside the cell walls. The hardness (H) of S2 cell wall layer slightly decreases, while the decrease of indentation modulus (E_r) is remarkable.

Key words: *wood modification; longitudinal compression; accordionisation; mechanical properties; wood bending.*

INTRODUCTION

The longitudinally compressed wood can be bent with lower forces in smaller curves till the break. A more suggestive naming is “accordionisation”, because the cell walls deform, crinkle during the process and finally seems like an accordion on the microscopic pictures (Fig. 1). The required bending force and the modulus of elasticity (*MoE*) decrease dramatically, and ensure a high deformability (Ivánovics 2006).

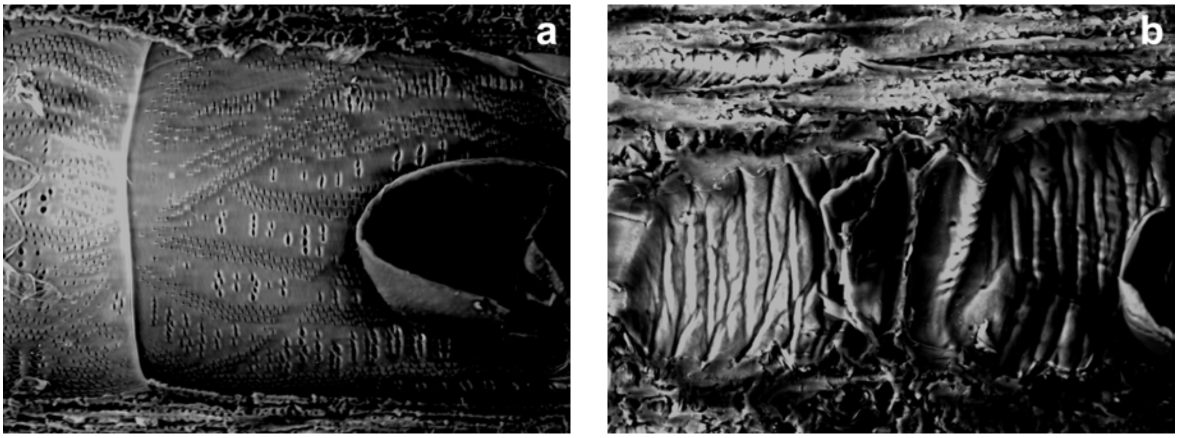

Fig. 1.
SEM photographs of the oak wood’s trachea in case of 2 samples (20 kV x200):
a – control; b – longitudinally compressed.

Mostly high quality hardwood raw material can be used for the process (Buchter 1993). Before the procedure the wood has to be plasticized by steaming. The moisture content of the raw material should be at least about the fiber saturation point (Báder and Németh 2016).

To provide the desired mechanical properties, the compression rate has to be equal along the entire length. Having markings along the sample’s length and measuring their distances before and after compression, the sections compression rate can be exactly specified.

The compression rate affects the mechanical properties of modified wood (Kuzsella 2011). In this research the compression rate was set to 20% according to the original length of the samples. After compression the sample can be hold for a while under pressure, this period is called relaxation. Mechanical tests were carried out to get the mechanical influence caused by longitudinal compression and different relaxation times.

OBJECTIVES

This series of researches was made to evaluate the effect of the longitudinal compression and the effect of the relaxation time on the properties of oak wood and beech wood. Untreated, steamed and longitudinally compressed samples were compared with 1 minute, 3 minutes, on occasion 5 minutes, and almost a day long relaxed wood samples. Such scientific examinations had never been published. This article is an overview of the preliminary results.

MATERIALS AND METHODS

Accordionisation

In this experiment Sessile Oak (*Quercus petraea* (Matt.) Liebl.) and Beech (*Fagus sylvatica* L.) wood species were used, from the highland near Sopron, Hungary. The dimension of the samples were always 200x20x20 m^3 (L x T x R), adapting to the compressing machine's capacity. For the longitudinal compression an excellent hardwood quality is needed: precise sized, knot- and defects-free, high moisture content and minimal fiber slope, free from cracks and deformations (Báder and Németh 2016).

After steaming at atmospheric pressure, the samples were compressed in the longitudinal direction by 20% in a semi-closed, tempered, unique laboratory machine, except the control ones. In Table 1 the used test methods can be seen for oak wood.

Table 1

Test methods and markings of the oak samples

Marking	Explanation
OC	Control
OSC	Steamed Control
O0m	Compressed without relaxation
O1m	Compressed with 1 minute relaxation
O3m	Compressed with 3 minutes relaxation
O5m	Compressed with 5 minutes relaxation
OLm	Compressed with a long-time relaxation

During relaxation phase the compression rate is kept persistent, but the pressing force is decreasing. In the first minute about with 30%, and the decreasing gradually slows down but the process still goes on even after a day (Báder and Németh 2017). At the *OLm* samples the heating of the laboratory compression chamber was switched off, so the samples did not lose much from their original humidity content.

Earlier investigations of Báder and Németh (2016) showed that unequal compression rate along the length befall very rare and in most cases if a mistake happens, the result is obvious, so the equal compression rate proof was not necessary at this investigation. Two cracked pieces of more than hundred samples were found, these were kept out from the next measurements.

Bending test

Before bending and nanoindentation tests, the control- and accordionisated samples were stored at normal condition (20 °C / 65%) until they reached the equilibrium moisture content.

The samples thickness (*h*) had to be cut back to 13,0 mm, to provide the proper support-span/specimen-thickness ratio (*L/h*) for the 4 point bending tests. In the Equation 1 the determination of the bending strength (*MoR*) can be seen, while the *MoE* and the maximum deflection (y_{max}) were determined with the Equation 2 and 3 by Kossa (2013).

$$MoR = \frac{3 \cdot F \cdot a}{b \cdot h^2} \ [MPa] \qquad (1)$$

where: F - maximum load, in N;
a - distance between the loading position and the nearest support, in mm;
b - width of the sample's cross section, in mm.
h - thickness of the sample's cross section, in mm.

$$MoE = \frac{\Delta F \cdot a^2 \cdot (3 \cdot L - 4 \cdot a)}{12 \cdot I_x \cdot \Delta w \cdot 1000} \ [GPa] \qquad (2)$$

where: ΔF - difference between the 10% and 25% of the maximum load, in N
L - distance between support span pins, in mm
I_x - second moment of area, in mm^4
Δw - increment of the load span displacement corresponding to ΔF, in mm.

$$y_{max} = \frac{F \cdot a \cdot (3 \cdot L^2 - 4 \cdot a^2)}{48 \cdot I_x \cdot MoE_y \cdot 1000} \, [mm] \tag{3}$$

where: MoE_y - bending modulus of elasticity belongs to the measured bending force at the moment of the breaking, in GPa.

Equation (3) was originally specified to get the y_{max} for low deflections, but our samples had high ones. With measuring the real deflection of some samples during the bending tests, we could obtain a linear supplemental equation (Equation 4):

$$y_{max\ real} = 1{,}1563 \cdot y_{max} - 0{,}7345 \, [mm] \tag{4}$$

where: $y_{max\ real}$ - real maximum deflection of the sample, in mm.

During bending the position of annual rings was in standing direction. The bending test of the control samples was made with 8mm/min load span displacement velocity, while the velocity at the compressed samples was 16mm/min, considering the greater deflection based on the Hungarian standard MSZ 6786-5:1976.

The specimens were kiln dried in a 103°C temperature oven to 0% moisture content after the bending test. Owing to the store in normal conditions, the moisture contents were all the same, about 14% at the time of the bending examinations. We used the general conversion method Equation (5) for the comparable mechanical properties.

$$\sigma_{12} = \sigma_u \cdot [1 + \alpha \cdot (u - 12)] \tag{5}$$

where: σ - measured mechanical property (in this case MoR and MoE)
α - a constant hanging on the type of the investigated mechanical property
u - moisture content, in %.

α=0,04 for the *MoR* and α=0,02 for the *MoE* (Kollmann 1951).

Nanoindentation

The small samples, required by the nanoindentation (NI) measurements were made from the middle part of the original samples. The originals were the *OC, OSC, O0m, O1m, O3m, OLm* oak, and *BC, BSC, B0m* beech samples. About 2x2mm^2 end grain surfaces were made, from the same annual ring, the latewood section. The small samples were embedded in epoxy resin by alternating vacuum-pressure. All moisture contents were between 9-10% at the time of embedding. They were dried at 60°C, then parallel surfaces were cut and glued to metal plates, perpendicular to the grain. A smooth surface was made for all samples with a Leica Ultracut-R microtome equipped with Trim 45° and Histo diamond knifes (Diatome, Switzerland).

The NI experiments were performed with a Hysitron Triboindenter® (Minneapolis, USA) and a Berkovich-type indenter tip. The mechanical properties of S2 cell wall layer were measured. The device imprints a tip in the selected point of the cell wall and measures the properties of the operation. The measured cell wall has to be at least 3µm thick. For example, the indentation modulus (E_r) and the hardness (H) of the cell wall can be obtained this way, using the Oliver and Pharr method (1992).

In each indentation process the tip reached the sample surface by a preforce of 2µN, then followed the test by three loading segments, as it is shown on the Fig. 2.

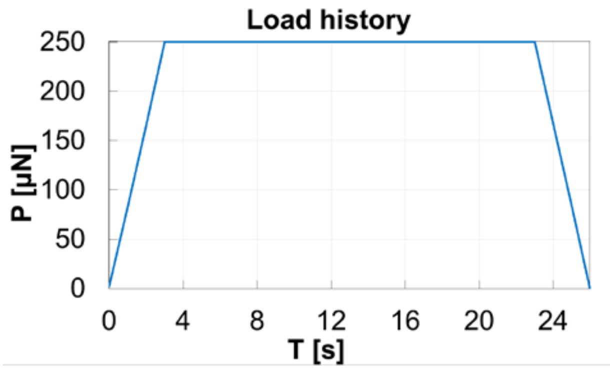

Fig. 2.
Nanoindentation load history.

The peak load (P_{max}) and the contact area (A) are recorded during the experiment. By dividing P_{max} by A, hardness can be calculated. The indentation modulus is determined from the initial slope of the unloading curve (Konnerth and Gindl 2006). E_r takes into account the compliance of the indenter tip. The influence of the diamond indenter's indentation modulus is negligible.

For NI the TriboScan v8.2.0.18 (Hysitron Inc, Minneapolis, USA) software was used. The 3D pictures were made with TriboView (Hysitron Inc, Minneapolis, USA) software. A typical example can be seen on the Fig. 3 for the appropriate NI measurements on a 15x15µm segment, with the imprints in the middle of the thick S2 wood cell wall around the lumen.

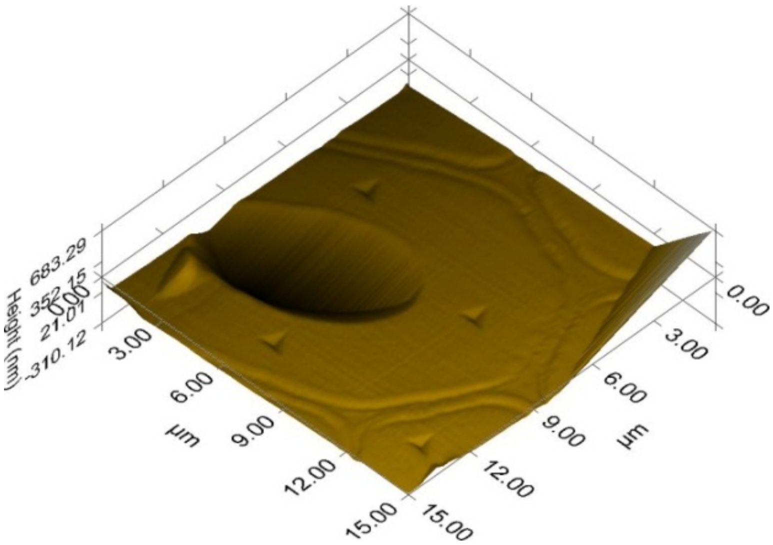

Fig. 3.
A nanoindented segment.

RESULTS AND DISCUSSION
Macromechanical changes

Four point bending tests were carried out as described above. The differences between the mechanical properties of control and modified samples are shown in Table 2.

Table 2

Changes in mechanical properties of the oak material during the accordionisation, compared to the control samples. Abbreviations: OC-control sample; OSC-steamed control sample; O0m, O1m, O3m, O5m-longitudinally compressed samples with 0, 1, 3 and 5 minutes relaxation time; OLm-compressed and long-time relaxed sample

Treatment name	Stress at 5 mm load span displace-ment	MoR	MoE
OC	100,0%	100,0%	100,0%
OSC	101,5%	102,2%	100,8%
O0m	46,8%	96,8%	41,5%
O1m	43,9%	95,4%	37,0%
O3m	41,5%	94,0%	34,2%
O5m	40,2%	93,1%	31,4%
OLm	29,3%	48,5%	18,6%

Between *OC* and *OSC* samples the differences are negligible. It can be clearly seen, that the stress at 5mm load span displacement and the *MoE* decrease to less than half of the original values by the longitudinal compression. With the relaxation time these two properties are decreasing further. However, *MoR* behave differently, just the long-time relaxation can cause a remarkable decrease. The long-time relaxation has an advantage, too. The *OLm* samples did not break in the course of the bending test. They could tolerate the highest deflection without breaking, this means their deflection ability is at least 6 times higher compared the deflection ability of control samples, while the maximum deflection of compressed and short-relaxed samples is 3-4 times higher than the deflection of control samples, till the break. The same bending rate needs much lower force by the accordionisation and the increasing relaxation time.

The change of the compressing stress during the relaxation is the highest in the first minute, more than 30% (Fig. 4). Leaving the first period the deflection of the compressing stress slows down, but does not stop. *OLm* samples lost about 75% of their original compressing stress.

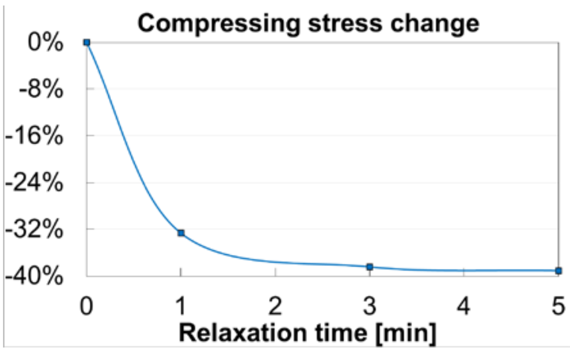

Fig. 4.
Change of the compressing stress in oak wood during relaxation.

Some physical and mechanical properties follow the behaviour of the compressing stress. *MoE*, stress at 5mm load span displacement and remaining length change are decreasing similarly, but does not have a great extent. This can be also seen in Table 2.

For the easier and higher deflection mostly the decreasing of MoE is responsible (Divos and Tanaka 2005, WPC 2011). The maximum deflection ability can be seen for control, longitudinally compressed and differently relaxed samples on the Fig. 5.

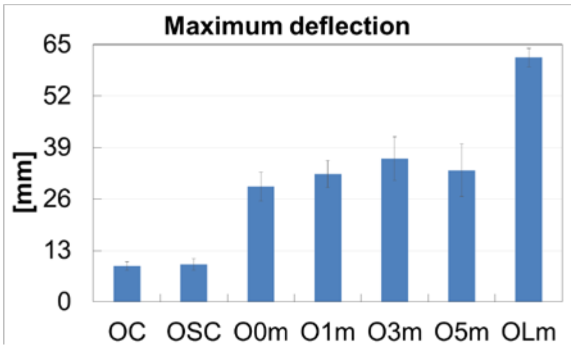

Fig. 5.
Maximum deflections for the control and the accordionisated materials. Abbreviations: OC-control sample; OSC-steamed control sample; O0m, O1m, O3m, O5m-longitudinally compressed samples with 0, 1, 3 and 5 minutes relaxation time; OLm-compressed and long-time relaxed sample.

The maximum deflection of *OC* and *OSC* control samples is similar. With the longitudinal compression the deflection multiplies, and finally the *OLm* group shows much higher deflection, compared to the control materials. The decrease of *O5m* samples deflection compared to *O3m* can be because of the lower sample number and the lower sample quality. However, this difference does not show a significant discrepancy. The ratios of the deflection (Fig. 5) are similar to the change of *MoE* in Table 2.

Micromechanical changes

On Fig. 6 can be seen well the difference between the effect of different treatments. While the steaming doesn't resulted great changes in the wood cell's indentation modulus, the longitudinal compression reduces E_r appreciably, with 25,0% for the oak and 21,0% for the beech cell walls. Short-time relaxations resulted in marginal changes in the E_r. However, long-time relaxation led to a great reduction again, by 34,8% more, according to the *O0m* group.

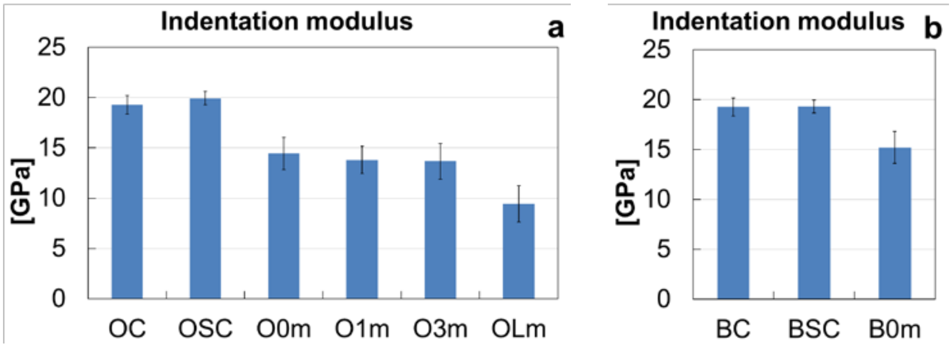

Fig. 6.
Indentation moduli of the control- and differently treated compressed samples: a – oak; b – beech wood. Abbreviations: OC and BC-control sample; OSC and BSC-steamed control sample; O0m and B0m, O1m, O3m-longitudinally compressed samples with 0, 1 and 3 minutes relaxation time; OLm-compressed and long-time relaxed sample.

Fig. 7 shows the changes in the same direction for hardness. The *H* of the cell walls decreasing with the accordionisation, but in smaller rate than the E_r. The difference between the hardness of *OC* and *O0m* groups is about 6,4% for the oak and 16,8% for the beech cell walls, and between *O0m* and *OLm* groups are 6,2% again. We can state, that hardness does not reduce as considerably as the E_r.

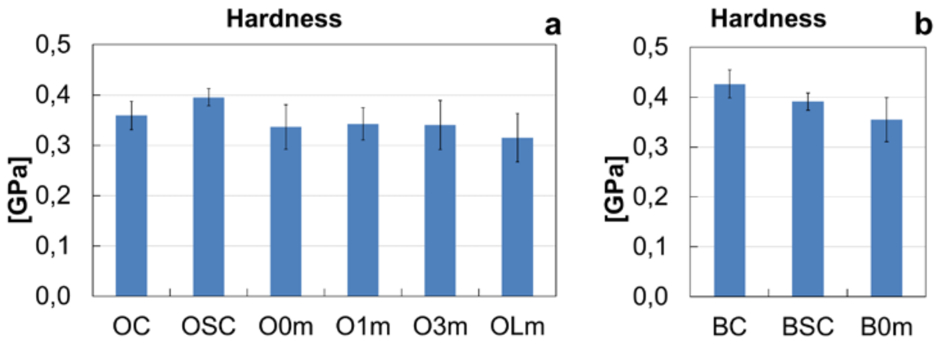

Fig. 7.
Hardness of the control- and differently treated compressed samples: a – oak; b – beech wood. Abbreviations: OC and BC-control sample; OSC and BSC-steamed control sample; O0m and B0m, O1m, O3m-longitudinally compressed samples with 0, 1 and 3 minutes relaxation time; OLm-compressed and long-time relaxed sample.

Due to the accordionisation which is a thermo-hydro-mechanical modification process, the structure of the cell walls change. In the bendability the elastic modulus plays the most important role. On cellular level the indentation modulus deflects greatly due to the accordionisation (*OC-O0m* 25,0% and *OC-OLm* 59,8%), but not so such a high degree as *MoE* on the macroscopic level (*OC-O0m* 58,5% and *OC-OLm* 81,4%). Also can be stated, that oak and beech wood species behave similarly to these modification processes.

CONCLUSIONS

The purpose of the longitudinal compression of wood, is to make the wood bendable. This study was performed to specify the changes of some main mechanical properties such as modulus of elasticity and some physical properties such as deflection of Sessile Oak, by the accordionisation and the different relaxation times.

Bending strength does not change remarkable by the modification, except the long-time relaxation it deflects to the half of the original value. However, stress at 5mm load span displacement deflects with 53,2% by the longitudinal compression and 70,7% due to the compression followed by a long-time relaxation. So bending to the same radius of an accordionisated, and even more a long-time relaxed wood needs much lower force. These values in the case of *MoE* are 58,5% and 81,4%, respectively. The latter fact explains the excellent bendability of this type of modified wood. On the cellular level also can be seen great changes in the value of indentation modulus, but not so greatly as on the macroscopic level (25,0% deflection for the accordionisation and 59,8% deflection for the long-time relaxation). The hardness of cell wall also decreases. Compression rate and relaxation time both significantly affect the mechanical properties of accordionisated wood.

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