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The Effect of the Rate of Longitudinal Compression on Selected Wood Properties

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Abstract – Longitudinal compression of wood and relaxation after compression (held compressed for a while) is called pleating and results in improved bending properties. The examinations conducted on the longitudinal compression of air-dried oak (*Quercus petraea* (Matt.) Liebl.) and beech wood specimens (*Fagus sylvatica* L.) revealed the effects of different compression rates (10, 20, 40, 60 mm/min). The comparison of the various treatment methods showed that the stress in wood specimens during longitudinal compression increases with the rising compression rate. The remaining length reduction due to pleating slightly decreases and the bending modulus of elasticity increases at higher compression rates. The highest deflection of the specimens during the 4-point bending tests lowers with the increasing compression rate, while the change of modulus of rupture is negligible. Taking into account the differences between these results and the industrial effectiveness of the treatment according to the compression rates, it can be stated that a procedure with a higher rate should be preferred.

wood modification / steaming / wood bending / pliability / MoE / MoR

Kivonat – A rostirányú tömörítés sebessége és a fa egyes tulajdonságai közötti kapcsolat. A faanyag hosszirányú összenyomása és az azt követő relaxáció (összenyomva tartás egy ideig) kiemelkedő hajlítási tulajdonságokat eredményez. Légszáraz tölgy (*Quercus petraea* (Matt.) Liebl.) és bükk minták (*Fagus sylvatica* L.) tulajdonságainak változását vizsgáltuk különböző tömörítési sebességek hatására (10, 20, 40, 60 mm/perc). Az eljárások összehasonlítása azt mutatta, hogy a mintákban keletkező feszültség a rostirányú tömörítés sebességének növelésével együtt növekszik. A maradandó hosszváltozás a tömörítés hatására kissé csökken, míg a hajlítórugalmassági modulus növekszik a nagyobb tömörítési sebesség hatására. A minták maximális behajlása a 4 pontos hajlítóvizsgálat során a növekvő tömörítési sebességgel csökken, míg a hajlítószilárdság változása elhanyagolható. Figyelembe véve az eredmények közötti különbségeket és a kezelés ipari hatékonyságát a tömörítési sebesség változásával megállapítható, hogy a nagyobb sebességű tömörítési eljárást célszerű előnyben részesíteni.

famodifikáció / gőzölés / fahajlítás / hajlíthatóság / MoE / MoR

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1 INTRODUCTION

At the beginning of the twentieth century, Hanemann (1917) patented the method of longitudinal compression of wood, and in the 1920s the technology suitable for serial production was also developed (Holzveredelung 1926). With this thermo-hydro-mechanical treatment, wood become more pliable, even in cold conditions, than it would be after only a steaming process. Longitudinally compressed wood can be used to make flexible and lightweight furniture (Anssary 2006), curved handrails with mechanical fastenings or edge bandings with gluing (Deibl et al. 1999), restoration work, vibration-dampened tool handles, custom-shaped tools, and arched picture frames. Longitudinally compressed wood can also be used in the construction, sports equipment, musical instrument, and visual arts industries (Vorreiter 1949). It can be processed with negligible wood waste (Ivánovics 2005, Anssary 2006), and no excessive manufacturing oversize is required. The structure of the compressed wood remains intact during shaping because the grain always follows the arch. According to our present knowledge, longitudinally compressed wood is currently produced in a few places around the world. In Italy, the Candidus Prugger SAS uses a technology patented in 1927, which was further developed by the company (Bátori 2000). In other places, manufacturers such as Compwood Products KFT (Hungary) and Pure Timber LLC (USA) use Compwood equipment developed in Denmark.

This method requires a high-quality hardwood raw material with at least middle-level density. After plasticization – using usually 100 °C saturated steam – the compression ratio is 15–25% of the original length. Following compression, the degree of compression should remain for a while to allow the relaxation of internal stress to further increase the compression effects. These changes slow down after 1 minute of relaxation, but do not cease *(Figure 1)*.

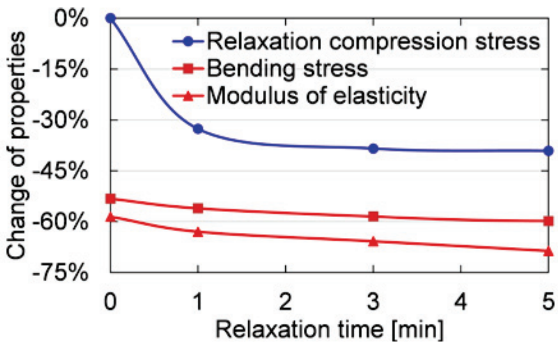

Figure 1. Some changes of oak wood due to 20% longitudinal compression are shown on the left side of the graph as well as the further change of these properties by relaxation (Báder and Németh 2018)

Longitudinal compression and 1-minute relaxation time results in an increase in maximum deflection during 4-point bending tests to 353%, and in a decrease to 37% in bending modulus of elasticity (*MoE*) and to 44% in bending stress at 5 mm crosshead displacement compared to the control specimens (Báder and Németh 2018). This means the process ensures high deformability for wood even with a dramatically decreased bending force. After treatment, the specimen is wet at the beginning, and as long as the moisture content (*MC*, [%]) is high, it can be bent more easily in a cold state when needed (Buchter et al. 1993). Different sources give different minimal moisture contents as a limit of pliability, ranging from 15% (Vorreiter 1949) to 25% (Buchter et al. 1993). During the modification process, the normally smooth cell walls deform (crinkle or buckle, *Figure 2*) (Báder and Németh 2017a). Therefore, this method may practically be called "pleating" (Báder and Németh 2018). While the moisture content is high, the wood is more pliable than it is in a dry condition, but it is always easier than uncompressed wood.

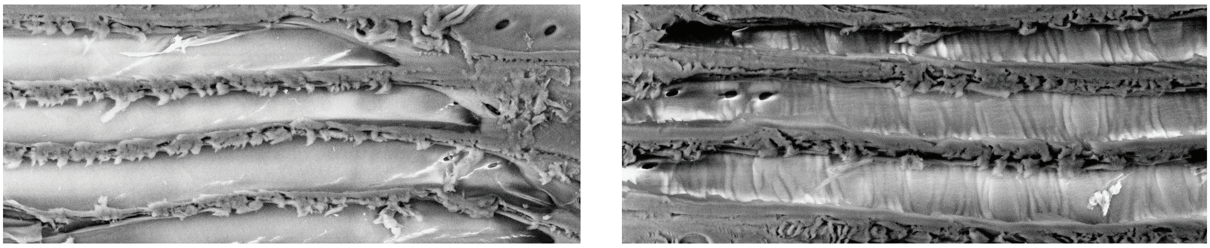

Figure 2. SEM images on radial sections of oak: before (left) and after (right) the longitudinal compression and relaxation treatment (magnification 1000x)

Unfortunately, scientific literature on this wood modification treatment is limited. Some studies contain general information about the technology and certain results (Vorreiter 1949, Heisel and Eggert 1990, Sandberg et al. 2013, etc.). Thorough studies of the physical and mechanical properties of this material are rare, and in many cases, they are found in theses (Bátori 2000, Sadatnejad et al. 2008, Kuzsella 2011, Báder and Németh 2018, etc.). In a previous experiment of Báder and Németh (2017c), applying a low compression rate (3 mm/min) to 200-mm-long specimens resulted in damage to 50% of the specimens. Generally, the fibers of the specimens bent out sideways and were thus unable to pass on the compression force in full length. However, at a compression rate of 6 mm/min, the yield was already 90%. On the other hand, high-speed compression, (for example 100 mm/min), rarely causes faults. However, operator intervention time is proportionally shorter in the event of specimen damage. If the specimen splits as a wedge due to a cross grain, it may damage the compression device. Taking these aspects into consideration, the compression rates have to be between about 6 and 100 mm/min (Báder and Németh 2017c). Further scientific articles relating to longitudinal compression rates were not found. The only sources that mentioned the topic were the book by Buchter et al. (1993) and some student theses (Bátori 2000, Sőregi 2007 and Dienes 2013).

The aim of this study is to determine the differences between the mechanical properties of pleated wood; these differences are caused by significantly different processing rates. This information can be used in the future to make disparate research results more comparable when the research is conducted under dissimilar circumstances. Furthermore, the properties of industrial products manufactured by similar methods will be more predictable.

2 MATERIALS AND METHODS

2.1 Specimen preparation

The raw materials for the experiment were sessile oak (*Quercus petraea* (Matt.) Liebl.) and beech (*Fagus sylvatica L.*) taken from the forests of the Sopron region in Hungary. The dimensions of the untreated, wet specimens determined by the laboratory scale compressing machine were 20×20×200 mm (R × T × L). The requirements for the specimens to be longitudinally compressed were that they be knot and defect-free, precisely sized hardwood cut from a tree with a straight trunk structure and free from cracks and tortuosity with minimal fiber slope (Báder and Németh 2016).

With the exception of the control specimens, steaming at atmospheric pressure was used for the plasticization of wood. After steaming, the specimens were longitudinally compressed in a self-engineered and individually produced device developed to operate in an Instron 4208 (Instron Corporation, USA) universal material testing machine. The workpiece is kept straight during the compression process through the supports on the sides of the machine. An internal temperature in the device of 90 to 100 °C – maintained by a thermostat – was adequate to keep the specimen in plasticized state. All specimens were compressed by 20% compared to their original lengths. To obtain information about the effects of compression rates in the margins and the middle region in the optimal range, the compression rates were set to 10, 20, 40 and 60 mm/min for the 200-mm-long specimens. Each group had 20 specimens of both wood species. After compression, the treated specimens were relaxed for 1 minute. Following the aforementioned treatments, the specimens were conditioned to 20 °C and 65% relative humidity until a constant weight was reached. Specimen *MC* was determined by a weight measurement method after the bending tests were completed. The *MC* relative to net dry weight can be calculated using the mass of the wet wood (m_n [g]) and the mass of the absolute dry wood (m_0 [g]), by the ISO 13061-1 (2014) standard (Eq. 1):

$$MC = \frac{m_n - m_0}{m_0} \cdot 100 \tag{1}$$

2.2 Measurements

Macromechanical experiments were performed with longitudinally compressed wood to acquire the discrepancies that different compression rates initiate. After conditioning, 4-point bending tests were conducted. Based on the method described by Báder and Németh (2018), the specimen height (*h*) was cut back to 12.5 mm, while width (*b*) was left at the original size. For the bending tests, specimens with an average 19.6×12.5 mm^2 (radial × tangential) cross section were used. The average length was 199.4 mm for the control specimens and 190.6 mm for the treated specimens, which resulted in an average 4.4% reduction due to pleating. The position of the annual rings was in vertical direction. An Instron 4208 (Instron Corporation, USA) universal material testing machine was used for 4-point bending tests. The loading rate was 8 mm/min for control specimens, and 20 mm/min for treated specimens according to Hungarian standard MSZ 6786-5 (2004). Tests were halted upon failure when the load dropped with no recovery. Modulus of rupture (*MoR*) with the 4-point bending test was determined by Eq. 2, according to the European standard EN 408 (2010) +A1 (2012).

$$MoR = \frac{3 \cdot F \cdot a}{b \cdot h^2} \tag{2}$$

where *F* is the maximum load, and *a* is the distance between the loading roller and the nearest support roller, which, in this case was 50 mm. The upper span was 50 mm as well. The calculation of *MoE* is based on the work of Báder and Németh (2018), using the increment of the crosshead displacement (Δw) corresponding to the 10% and 25% difference of the maximum load (ΔF) in Eq. 3.

$$MoE = \frac{\Delta F \cdot a^2 \cdot (3 \cdot L - 4 \cdot a)}{12 \cdot I_x \cdot \Delta w} \tag{3}$$

where *L* is the lower span and I_x is the second moment of area. y_{max} is the maximum deflection during the bending test, which came from Eq. 4 (Báder and Németh 2018).

$$y_{\max} = 1.1563 \cdot \frac{F \cdot a \cdot (3 \cdot L^2 - 4 \cdot a^2)}{48 \cdot I_x \cdot MoE_y} - 0.7345 \tag{4}$$

where MoE_y is the bending modulus of elasticity, which belongs to the bending force and the deflection measured at the end of the bending test. Eq. 4, modified with experimental values, is applicable for highly pliable wood materials. After the bending test, the specimens were analyzed visually, and their *MC* was determined by drying the specimens to 0% *MC* in an oven at a temperature of 103±2 °C. As the mechanical properties of wood change with the *MC* , the mechanical properties of the specimens were recalculated to get comparable results at 12% *MC* as described in Eq. 5, according to standard series ISO 13061 (2014).

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

where σ_{12} is the mechanical property at 12% *MC*, σ_u is the examined mechanical property at the *MC* at the time of measurements, u is the *MC* of wood at the time of measurements. α is the coefficient of moisture dependence of mechanical properties, and it has been determined for treated wood specimens as 0.04 for the modulus of rupture and 0.05 for the modulus of elasticity. The equilibrium moisture content at the time of the bending examinations averaged between 9.3% and 9.8% for beech specimens, and between 7.6% and 9.8% for oak specimens.

3 RESULTS AND DISCUSSION

3.1 Physical properties

Several machines have been developed for longitudinal wood compression; some of these are in use today. These machines differ in capacity (both in length and cross-section) and compression technology, which determines the compression rate. Therefore, it is necessary to obtain a universal unit of measurement for the rate of longitudinal compression to make the comparison on laboratory measurements and different industrial scales possible. It seems best to use the relative rate of compression $\left[\frac{m}{m \cdot h}\right]$, as it provides information that is independent of the specimen size (Báder and Németh 2017c). Basic units are used to show how much shortening would occur in a 1-meter-long section of the workpiece during a 1-hour compression process. In other words, it represents the amount of shortening that occurs on the workpiece per unit length over a unit of time. The relative rate of compression described above is independent of the compression ratio. Since the latter is also a significant factor, it is advisable to specify the percentage of shortening relative to the original length. The rate of longitudinal compression is extremely important for both productivity and quality output. Using the relative rate of compression and the data from literature, it can be calculated that industrial equipment working with large raw material cross-sections and lengths compress at a rate of 0.4 to 2.4 $\frac{m}{m \cdot h}$ (Buchter et al. 1993, Bátori 2000, Sőregi 2007, Dienes 2013). The laboratory equipment (Báder and Németh 2017b) can successfully compress small specimens with dimensions of 20x20x200 mm^3 at a rate of 1.8 to 30 $\frac{m}{m \cdot h}$. Further refining these values, according to Báder and Németh (2016), it is recommended to use a productive but safe 9 to 15 $\frac{m}{m \cdot h}$ compression rate that allows a better than 90% yield. In this study, using the unit of measurement of the relative rate of compression, 3, 6, 12 and 18 $\frac{m}{m \cdot h}$ compression rates were used.

During the longitudinal compression process, the compression force increases gradually until the end of the compression phase, and during the following relaxation, it decreases in the first minute by 1/3 compared to the maximum value (Báder and Németh 2018). The results of the examinations show that the maximum compression stress increases with the compression rate, while during relaxation, the decrease of the compression stress gets higher with the increasing compression rate *(Figure 3)*.

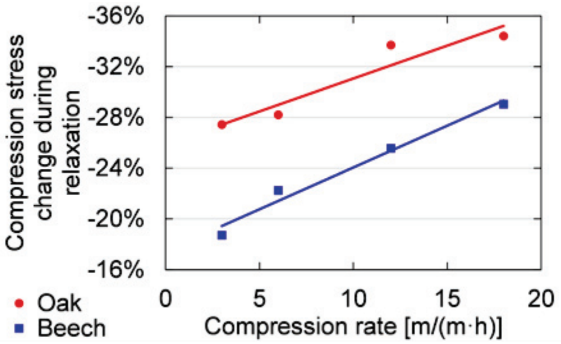

Figure 3. The change of compression stress during 1 minute of relaxation time, as a function of the compression rate

Although the change of compression stress during 1-minute relaxation time of oak and beech wood were similar, the test results for ring-porous oak and diffuse-porous beech wood often showed different tendencies. The coefficient of determination for the remaining length change by pleating is very good in the oak specimens (0.95), but weak in the beech specimens (0.01) *(Figure 4a)*. Based on the results of previous studies (Báder and Németh 2017c), under a certain rate it is not possible to achieve proper compression quality. The lowest compression rate of beech data point seems to be an outlier. Both oak and beech are hardwoods, but they have significantly different structures. Hence, it is likely that oak can already be sufficiently compressed at this rate, but in the case of beech, this rate is still too low for a successful longitudinal compression. If this result is ignored, the coefficient of determination will be 0.83 *(Figure 4b)*. Accordingly, the results of the lowest compression rate of beech will be further illustrated for information purposes only. Furthermore, it is worth noting that the deviation of the results of beech wood is always higher than the deviation of oak results; therefore, oak provides more reliable material properties. Higher remaining length reduction due to pleating indicates an increase in the bending modulus of elasticity (*MoE*) and better pliability, according to Báder and Németh (2018). By increasing compression rate, the length reduction will be lower, which means a decrease in the success of the treatment, as described hereinafter.

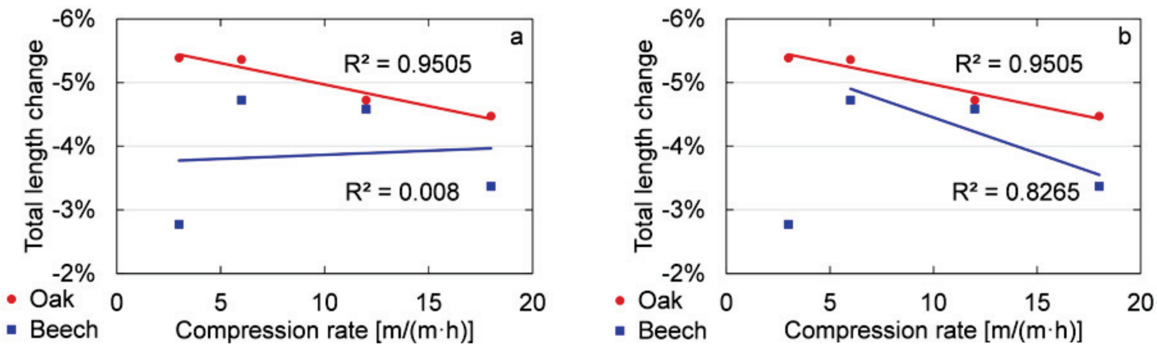

Figure 4. Remaining length change by pleating and conditioning as a function of the compression rate. For the linear trend lines, all the data points were taken into account (a) and the lowest compression rate of beech was not taken into account (b)

3.2 Mechanical properties

Based on the results of Ivánovics (2006) and Kuzsella and Szabó (2006), the average decrease of the modulus of rupture (*MoR*) was 29% for oak and 47% for beech wood due to 20% longitudinal compression. The results of this study were lower, with a 21-25% decrease at a 20% compression ratio and 1-minute relaxation. The difference may be attributed to a dissimilar relaxation process, a different bending test method, and the natural diversity of wood. In *MoR*, a 5% increase for oak and 1% decrease for beech is observable with a 20% compression ratio and 1-minute relaxation time, between 3 and 18 $\frac{m}{m \cdot h}$ compression rates *(Figure 5a)*. These changes are so low that they can be considered negligible. The bending stress during 4-point bending tests behaves the same as *MoR*, but *MoE* has a higher slope for both oak and beech wood *(Figure 5b)*.

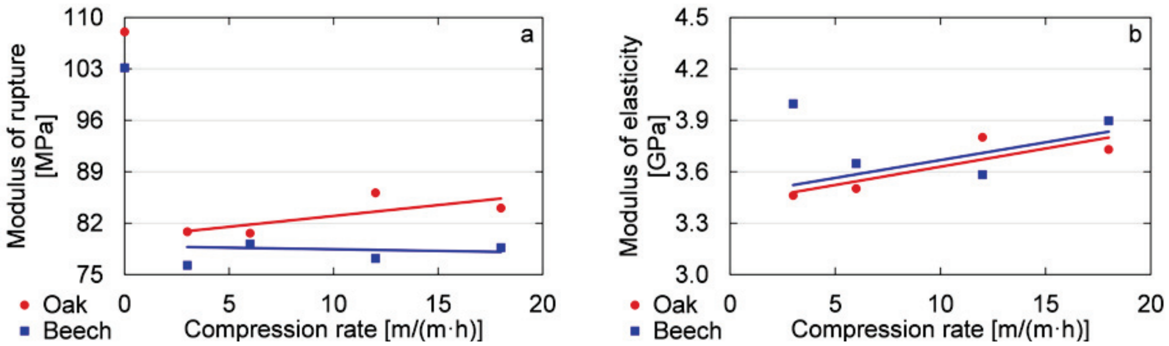

Figure 5. The modulus of rupture (a) and the modulus of elasticity (b) as a function of compression rate

The *MoE* for beech control specimens was 9.2 MPa, and for oak control specimens, it was 9.8 MPa. The decreases of *MoE* were between 58% and 62%, and between 61% and 64%, respectively. These values correlate with the published data (Vorreiter 1949, Ivánovics 2006, Kuzsella and Szabó 2006, Báder and Németh 2017d, etc.). Compared to the control specimens, the increase of *MoE* was about 3% with the change of the compression rate. However, considering only the *MoE* of treated specimens as a function of the compression rate, it is 9% for both wood species. Báder and Németh (2018) found that the *MoE* of oak correlates well inversely with pliability. Accordingly, the decrease of deflection at maximum load during 4-point bending test is 9% between 3 and 18 $\frac{m}{m \cdot h}$ compression rate for oak, and 22% for beech wood. The higher value for the deflection decrease was indicated by the higher change of compression stress during relaxation *(Figure 3)* and the higher length change by pleating *(Figure 4b)*. This property is a result of the characteristics of beech wood. Beech, more than oak, responds differently to the same treatment and changes in circumstances. The deflection at maximum load is between 428% and 334% for beech and between 462% and 422% for oak in the compression rate range that was used, compared to the deflection of the control specimens *(Figure 6)*. The available flexibility is thus high – at least 3–4 times higher because of the pleating. However, with further adjustments for the treatment, at least 2 times higher flexibility is available (Báder and Németh 2018).

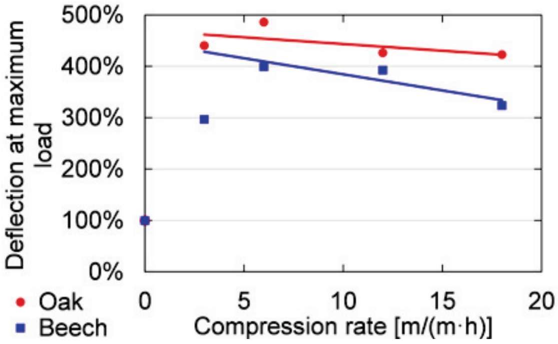

Figure 6. The change of deflection at maximum load during 4-point bending test, as a function of compression rate

Considering the increase in the production speed of compressed wood and, consequently, both the productivity growth and cost reduction as a function of the deterioration of flexibility, higher compression rates are acceptable. Of course, if there is a demand for the highest achievable flexibility, a lower compression rate, higher compression ratio, and much higher relaxation time should be used (Báder and Németh 2018).

4 CONCLUSIONS

In this study, the effect of the compression rate on the mechanical properties of ring-porous oak and diffuse-porous beech hardwoods was investigated. A new unit of measurement, the use of the relative compression rate $\left[\frac{m}{m \cdot h}\right]$ became necessary. It represents the shortening that occurs on the workpiece per unit length over a unit of time. Compression rates between 3 and 18 $\frac{m}{m \cdot h}$ were used. The stress in wood specimens during longitudinal compression increases with the increasing compression rate, and the remaining length reduction is lowered. The specimens were subjected to 4-point bending tests. The change of modulus of rupture is not significant with increasing compression rates as well as the change of bending stress. For both oak and beech specimens, the modulus of elasticity increases by 3% in this range of compression rate. The deflection at maximum load decreases by 9% for oak and by 22% for beech, but still remains very high compared to the untreated wood. If the effectiveness of the treatment according to the compression rates is considered, higher compression rates should be preferred. If a higher flexibility is needed, higher compression ratios and longer relaxation times are more effective.

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