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Influence of longitudinal compression rate on the properties of wood

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ABSTRACT

Longitudinal compression of wood and relaxation after compression (held compressed for a while in the press) is called pleating, due to the crinkling of cell walls by the treatment. This modification process results in improved bending properties. The maximum deflection during bending tests increases by pleating, while the needed force to reach the same deflection decreases, compared to untreated samples, similarly to the bending modulus of elasticity. The modulus of rupture does not change considerably by pleating and short-time relaxation. The examinations conducted on the longitudinal compression of air-dried oak (Quercus petraea (Matt.) Liebl.) and beech wood samples (Fagus sylvatica L.) revealed the effects of different compression rates (10, 20, 40, 60 mm/min). The mechanical properties of both untreated and modified wood samples were subjected to 4-point bending tests. The comparison of the various methods of treatment showed that the stress in wood samples during longitudinal compression increases with the increasing 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 samples during the 4-point bending tests lowers with the increasing compression rate. As an influence of the higher compression rate, the modulus of rupture decreases less. 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 higher rate should be preferred.

1 INTRODUCTION

The combined thermo-hydro-mechanical compression along the wood grain (also known as longitudinal compression or pleating) (Báder and Németh 2017a) results in bendable wood. With longitudinal wood compression, the required bending force and the modulus of elasticity decrease dramatically and provide great bendability to the wood.

The procedure requires high quality hardwood material, as well as the Thonet-method. Before compression, the wood has to be plasticized by steaming. The softening temperature of wood is 80°C (Lenth and Kamke 2001), so the usually used 100°C saturated steaming of the samples is an appropriate pre-treatment. In a previous experiment (Báder and Németh 2017c), the use of a low compression rate (3 mm/min) resulted in damage to 50% of the samples. Usually the fibers of the samples bent out sideways and were not able to pass on the compression force in full length. But 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, in case of sample damage, the time for the operator's intervention is proportionally shorter. If the sample splits as a wedge due to 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). After longitudinal compression, the sample can be held compressed for a while, allowing the wood to undergo viscoelastic relaxation. This means the sample is compressed for example to 20% of its original length, and this compression ratio is kept constant for a predetermined time. The sample is wet at the beginning, and as long as the moisture content is high, it can be bent more easily. Different sources give different minimal moisture contents as a limit of bendability, ranging from 15% (Vorreiter 1949) to 25% (Buchter et al. 1993).

Relaxation further enhances the bending properties of wood. After 1 minute of relaxation, these changes slow down, but do not cease. Relaxation time can be up to a day long and this produces very different properties for the wood, for example an increment of more than 200% deflection compared to the compressed samples during the 4-point bending test, still without breaking (Báder and Németh 2018). Wood has a memory-effect. After longitudinal compression, shortening by a few percentages appears, and with the increasing relaxation time, shortening also increases (Figure 1) (Báder and Németh 2018).

Figure 1. Shortening of samples from different treatments. Abbreviations: OC – control sample; O0m – longitudinally compressed sample; O1m – longitudinally compressed sample relaxed for 1 minute; OLm – longitudinally compressed sample relaxed for 18 hours.

Considering the changes in mechanical properties and technological time, 1 minute relaxation time is recommended (Báder and Németh 2018).

2 MATERIALS AND METHODS

2.1 Raw material

The raw materials of the experiment were sessile oak (*Quercus petraea* (Matt.) Liebl.) and beech (*Fagus sylvatica L.*), from the forests of the Sopron region in Hungary. The dimensions of the untreated, wet samples were 20x20x200 mm (radial x tangential x longitudinal), determined by the laboratory scale compressing machine. The requirements of the samples to be longitudinally compressed are to be knot and defect-free hardwood, precisely sized, free from cracks and tortuosity with minimal fiber slope, cut from a straight grown tree (Báder and Németh 2016).

2.2 Longitudinal compression and relaxation

For the plasticization of wood, steaming at atmospheric pressure was used, except for the control samples. After steaming, the samples 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. The internal temperature of 90 to 100 ° C in the device – maintained by a thermostat – was adequate to keep the specimen in plasticized state. All samples were compressed by 20% compared to their original lengths. To get information of 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 samples. Each group had 20 samples of both wood species. After compression, the treated samples were relaxed for 1 minute. After the aforementioned treatments, the samples were conditioned to 20 °C and 65% relative humidity, until a constant weight was reached.

2.3 Bending test

Macromechanical experiments were performed with longitudinally compressed wood, to get the discrepancies that different compression rates initiate. After conditioning, 4-point bending tests were carried out. Based on the method described by Báder and Németh (2018), the height of the samples (*h*) was cut back to 12.5 mm, while the width (*b*) was left to the original size. For bending tests, samples with averagely 19.6×12.5 mm^2 (radial × tangential) cross-section were used. The length was averagely 199.4 mm for control samples, and 190.6 mm for treated samples, which means averagely 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 samples, and 20 mm/min for treated samples according to Hungarian standard MSZ 6786-5 (2004). Tests were stopped upon failure, when the load dropped with no recovery. Modulus of rupture (*MoR*) with 4-point bending test was determined according to the European standard EN 408 (2010) +A1 (2012).

The determination of the bending modulus of elasticity (*MoE*) comes from the work of Báder and Németh (2018), using the increment of the crosshead displacement (Δw) corresponding to the difference between the 10% and 25% of the maximum load (ΔF) in Eq. 1.

$$MoE = \frac{\Delta F \cdot a^2 \cdot (3 \cdot L - 4 \cdot a)}{12 \cdot I_x \cdot \Delta w} \quad (1)$$

where L is the lower span and I_x is the second moment of area. The maximum deflection during the bending test (y_{max}) came from Eq. 2 (Báder and Németh 2018).

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

where F is the maximum load, and a is the distance between the loading roller and the nearest support roller, in this case 50 mm. The upper span was also 50 mm. MoE_y is the bending modulus of elasticity, which belongs to the bending force measured at the end of the bending test. Eq. 2, modified with experimental values, is applicable for highly bendable wood materials. After the bending test, the samples were analyzed visually, and their moisture content was determined by drying the specimens to 0% moisture content, in an oven at a temperature of 103±2 °C. As the mechanical properties of wood change with the moisture content, the mechanical properties of the samples were recalculated to get comparable results at 12% moisture content, as described in Eq. 3, according to standard series ISO 13061 (2014).

$$\sigma_{12} = \sigma_u \cdot [1 + \alpha \cdot (u - 12)] \quad (3)$$

where σ_{12} is the mechanical property at 12% moisture content, σ_u is the examined mechanical property at the moisture content at the time of measurements, u is the moisture content 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 samples 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 was averagely between 9.3% and 9.8% for beech samples, and between 7.6% and 9.8% for oak samples.

3 RESULTS AND DISCUSSION

3.2 Compression rate

Several machines have been developed for longitudinal wood compression and a few of them are working 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 possible the comparison on laboratory measurements and different industrial scales. It seems to be the best to use the relative rate of compression $\left[\frac{m}{m \cdot h}\right]$, as it provides information that is independent of the sample 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 samples 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 9.0 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, 3.0, 6.0, 12 and 18 $\frac{m}{m \cdot h}$ compression rates were used.

During the longitudinal compression process, the compression force increases gradually till 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 2).

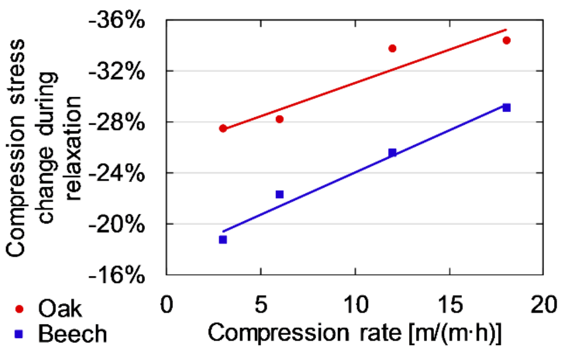

Figure 2. The change of compression stress during 1 minute relaxation time, as a function of the compression rate.

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 samples (0.95), but weak in the beech samples (0.01) (Figure 3a). 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 data point of the lowest compression rate of beech seems to be an outlier. Both oak and beech are hardwoods, but they have significantly different structures, so it is likely that oak can be already 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 3b). Accordingly, the results of the lowest compression rate of beech will be further illustrated for information 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 bendability, 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.

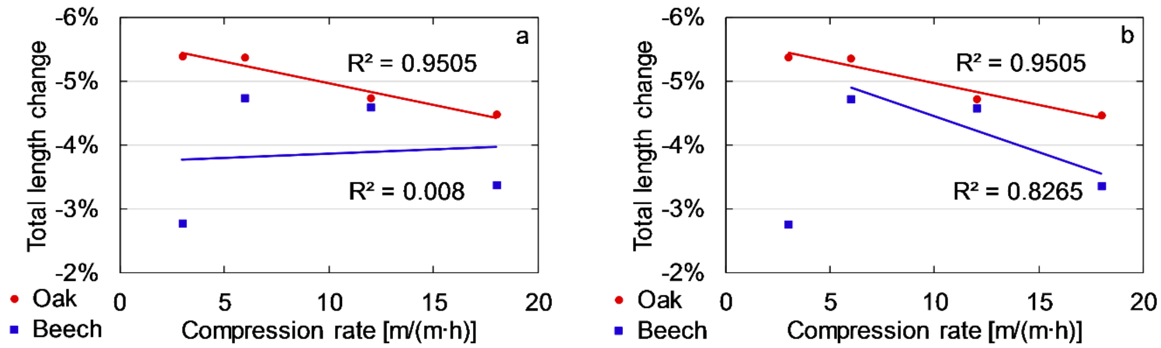

Figure 3. Remaining length change by pleating and conditioning, as a function of the compression rate. For the linear trend lines, all the data points were taken into account (a) and the lowest compression rate of beech was not taken into account (b).

3.3 Bending tests

The modulus of rupture (*MoR*) was averaged a 29% decrease for oak and 47% decrease for beech wood by Iványovics (2006) and Kuzsella and Szabó (2006) due to 20% longitudinal compression. the results were less with a 21-25% decrease at a 20% compression ratio and 1 minute relaxation. The difference can be the result of a different 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 increasing compression rates, between 3 and 18 $\frac{m}{m \cdot h}$ (Figure 4a). 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 4b).

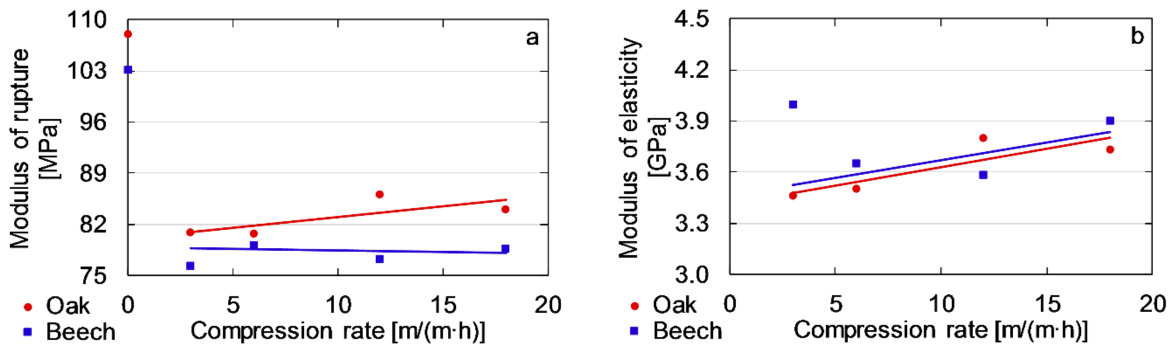

Figure 4. The modulus of rupture (a) and the modulus of elasticity (b) as a function of compression rate.

The *MoE* for beech control samples was 9.2 MPa, and for oak control samples, it was 9.8 MPa. The decrease of *MoE* with a 20% compression ratio at different compression rates and 1 minute relaxation were between 58% and 62%, and between 61% and 64%, respectively. These values correlate with the published data (Vorreiter 1949, Iványovics 2006, Kuzsella and Szabó 2006, Báder and Németh 2017d, etc.). The increase of *MoE* was about 3% with the change of the compression rate, compared to the control samples. However, considering only the *MoE* of treated samples 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 bendability. 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 2) and the higher length change by pleating (Figure 3b). This property is a result of the characteristics of beech wood. It responds to the same treatment and changes in circumstances differently, more than oak. 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 samples (Figure 5). The available flexibility is thus high, at least 3-4 times higher as a result of the pleating. However, with further adjustments for the treatment, at least 2 more times higher flexibility is available (Báder and Németh 2018).

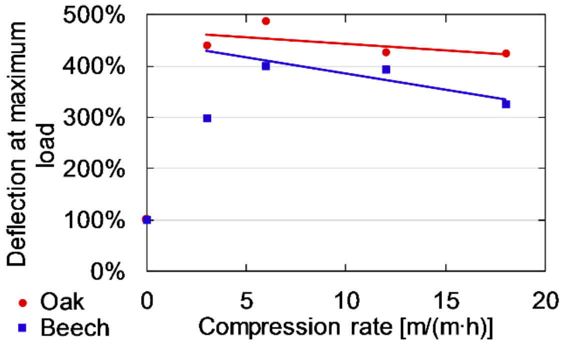

Figure 5. The change of deflection at maximum load during 4-point bending test, as a function of compression rate.

Taking into account the increase in the speed of production of the compressed wood and, consequently, both the growth of productivity and the reduction of costs 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, a higher compression ratio and a 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 samples during longitudinal compression increases with the increasing compression rate, and the remaining length reduction is lowered. The samples 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. The modulus of elasticity increases 3% in this range of compression rate, for both oak and beech samples. The deflection at maximum load decreases by 9% for oak and 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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