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COMPRESSIVE STRENGTH OF THERMO-HYDRO-MECHANICALLY MODIFIED SAMPLES AT DIFFERENT MOISTURE CONTENTS

Mátyás Báder[0000-0002-1242-7664 1*], *Pál Péter Gecseg*[0009-0001-4450-3350 1]

[1] University of Sopron, Faculty of Wood Engineering and Creative Industries, Bajcsy-Zs. Str. 4, Sopron, Hungary
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Abstract
This study presents the steps and results of the longitudinal compression modification process (aka. pleating) and compression tests of sessile oak wood (Quercus petraea (Matt.) Liebl). Compression tests were done to determine properties under different moisture conditions. The stress values during the pleating of the specimens were nearly identical, attributed to proper pre-selection of the specimens. Regarding compressive strength, the average values were approximately 40.94 MPa for the pleated frozen samples, 55.55 MPa for the pleated groups conditioned to 12% moisture content, 93.66 for the pleated group conditioned absolute dry and 55.46 MPa for the untreated group conditioned to 12% moisture content. In terms of compressive modulus of elasticity, the average values were approximately 0.11 GPa, 1.76 GPa, 3.12 GPa and 3.08 GPa, respectively.

1 Introduction

The purpose of longitudinal compression (or pleating) timber is to make it more flexible and pliable. Treating wood as an inhomogeneous fibre-reinforced composite, pre-plasticization, and compression along the fibres result in higher bendability with less force. Steam bending of wood was first used for large-scale production by Michael Thonet in the 19th century [1]. In Thonet's method, wood must be immediately shaped after steaming before it cools. In contrast, the advantage of pleating technology is that the treated timber can be stored and remains bendable at room temperature. Hardwood species with higher density (e.g. oak, beech, ash, maple) have been found to be compressible along the grain. High-quality raw material is essential, as wood failures can often cause significant problems during the modification process. Key factors determining the production of pleated timber include wood species, quality of raw material, moisture content (*MC*), temperature, compression ratio, and others. Most hardwood species with higher density and initial *MC* above 20% can be pleated. During the compression process, the softened wood has to be kept at a temperature of at least 80°C. It is necessary to support the wood to prevent lateral deflection and reduce friction forces that inhibit uniform compression along the fibres. As a result of pleating, changes occur in the cell structure of the wood. The middle layer, mainly composed of lignin and hemicellulose, supports the high cellulose content, solidifying fibres, and other tissues to slide relative to each other, while the cell walls of these longitudinally oriented elements become wrinkled (*Figure 1*). As a result of the process, the bending modulus of elasticity (*MoE*) of the wood highly decreases, making it significantly more bendable compared to untreated wood [2], [3].[*]

*Corresponding author.
E-mail address: bader.matyas@uni-sopron.hu

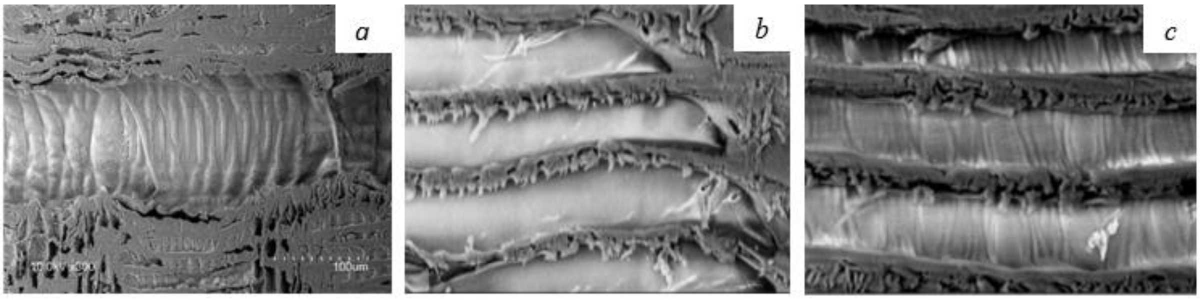

Figure 1. Changes in vessels and fibres during compression: pleated vessels (a), unpleated fibres (b) pleated fibres (c) (based on Németh et. al. [4], Báder and Németh [5])

Wood contains water in two forms: free water and bound water. Free water exists in the wood as liquid or vapour and has a significant impact on the wood's mass and density. However, it does not affect the wood's shape, size and the most mechanical properties. The removal of bound water begins only after the evaporation of free water. The point at which there is no free water left in the cell structure of the wood is called the *FSP*. While the value of the *FSP* depends on the wood species, generally, the portion of *MC* below 30% is considered bound water, and the *MC* above 30% is referred to as free water [6].

Under compressive loading, the load on the sample shortens its size in the direction of the force. A pure compressive loading occurs when the dimensions of the specimen parallel to the direction of loading do not exceed three times the dimensions of the cross-section subjected to the loading. A specimen longer than this may buckle. Compressive loading is a common load in various wood structures. Furniture frames and supporting structures of buildings are subjected to compressive loads parallel to the grain, and floor coverings and sleepers are subjected to compressive loads perpendicular to the grain. Compressive strength (*CS*) occur under bending loads, too. The *CS* of solid wood parallel to the grain is several times (about 5 to 7 times) higher than perpendicular to the grain. Knots, twisted growth, high degree of warpage and other wood defects reduce the *CS* in the direction of the fibre. A 1% increase in bonded water causes a 4-5% decrease in *CS*. The average air-dry *CS* of domestic wood species is 25-80 MPa. Three types of perpendicular *CS* are distinguished: total surface *CS*, partial/sleeper *CS* and local *CS* that affects only part of the sample length and width. Due to the different types of stresses, both partial and local *CS* are significantly higher (50-80%) than the total surface *CS*. The *CS* of engineered products (chipboard, fibreboard) parallel to the plane is lower than that of solid wood. The *CS* of plywood is on average lower parallel to the plane, but higher perpendicular to the plane, than that of solid wood [7], [8], [9]. Our study aims to demonstrate the changes that pleated oak wood undergoes solely due to variations in *MC*. We primarily examined these changes through compression tests, as we were particularly interested in understanding the differences in compression properties of wood in response to changes in *MC*.

2 Materials and Methods

As a first step, we selected 10-10-10 pieces of suitable, 20×30×200 mm (thickness × width × fibre direction) dimensioned sessile oak (*Quercus petraea* (Matt.) Liebl.) mature wood specimens for each sample. Care was taken to ensure that the wood was free from failures, as these would have led to inaccuracies in the measurements. Examples of such failures include slope of grain, knots, cracks, etc. Subsequently, the specimens were numbered for tracking purposes (*Figure 2*), followed by the pleating of the wood. The pleating was performed using an INSTRON 4208 material testing machine (INSTRON Corp., USA). Prior to compression, the samples were steamed for 45 minutes at 100 °C temperature. Compression was carried out in closed equipment at a rate of 25%/min, then the specimens were kept in a compressed state for 1 minute. The test setup and the compression process detailed can be found in the study of Báder and Németh [3]. After pleating, if a specimen was bent, it was manually straightened.

Figure 2. Images of some specimens after pleating (left) and after cutting for compression test (right)

Once the pleating was complete, the specimens were conditioned and cut into smaller pieces, preparing the compression test specimens. The longitudinal dimensions of the compression test specimens were 17 mm, while their thickness and width were 11 x 11 mm according to the modified dimensions in the standard ISO 13061-17 [17]. The sample with *MC* above *FSP* was stored in a freezer to maintain its green state, the pleated sample was conditioned to 12% *MC* and the untreated sample was stored in a climate chamber at 20 °C and 65% relative humidity, while the absolute dry sample was stored in a dryer (Memmert UFP 500) at 103 °C.

The compression tests were also done on the INSTRON 4208 material testing machine. For the measurement, we used different loading rates. For the pleated samples we used 2 mm/min, and for the untreated sample we used 0.4 mm/min rate. This was necessary to comply with the requirements of ISO 13061-17 [10] standard, which require a compression testing time between 1 and 5 minutes. Every sample contained 20 specimens. During the test, the specimens were in the middle of a metal support. Prior to each test, width and thickness parameters were measured at the centre of the specimen. Upon completion of the compression tests, we compared and evaluated the collected data. Conclusions were drawn from the measurements involving the average results and relative deviances of the *CS* and the compression modulus of elasticity (*CMoE*).

3 Results and discussion

During pleating, the average values of maximum compressive stress were 21.03 MPa for the pleated and frozen sample, 19.41 MPa for the pleated 12% *MC* conditioned sample and 21.27 MPa for the pleated and dried sample. The relative deviations were 7.3%, 7.1% and 14.1%, respectively. Accordingly, the results of the specimens did not show significant differences. This indicated that we had performed appropriate raw material selection before pleating, ensuring that the specimens were similar anatomically and physically. Consequently, the differences obtained from the mechanical tests were not due to the wood itself but rather to differences in the *MC* of the specimens. The average *CS* was 55.55 MPa for the pleated sample conditioned to 12% *MC*. In comparison, the pleated sample frozen above *FSP* showed 26.3%lower *CS*, the pleated absolute dry sample showed 40.7% higher *CS*, while the untreated sample conditioned to 12% *MC* had negligible difference (*Figure 3*).

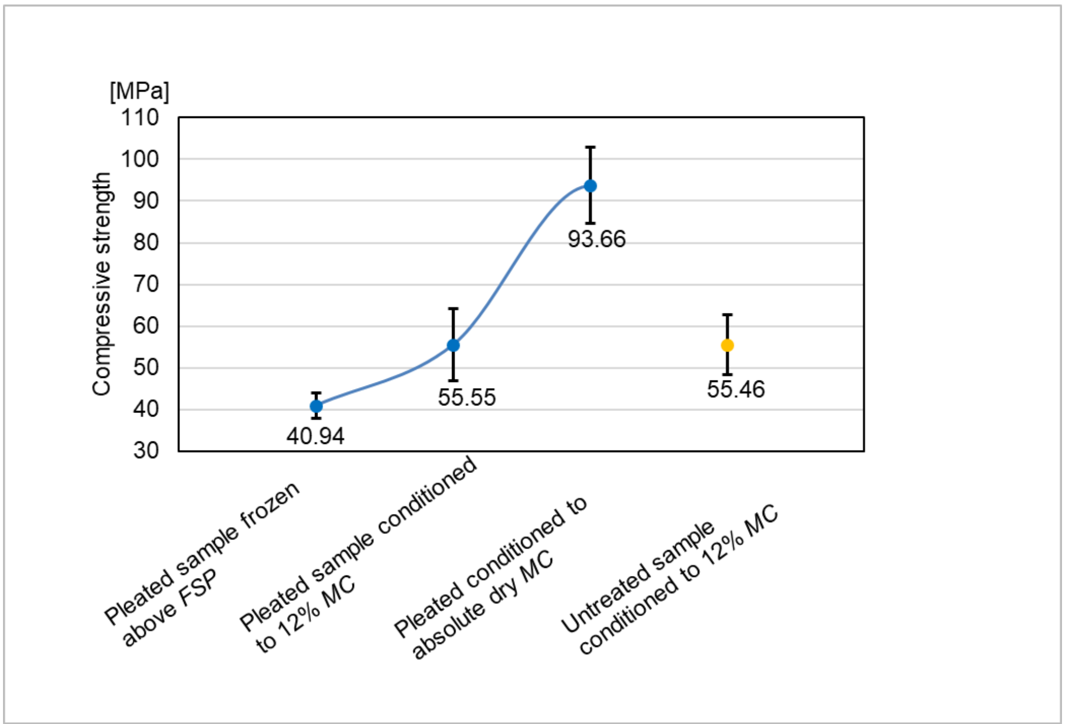

Figure 3. Compressive strength of the samples. Abbreviations: FSP – fibre saturation point; MC – moisture content

We attribute the observed changes in the measurements to lignin and hemicellulose in the wood, as they behave more plastically with higher *MC*. For *CS* the data shows that the pleating has no effect on the results. The average values of the *CMoE* were only 0.11 GPa for the pleated and frozen sample, 1.76 GPa for the pleated and conditioned to 12% *MC* sample, 3.12 GPa for the pleated and conditioned to absolute dry sample and 3.08 GPa for the untreated sample at 12% *MC* (*Figure 4*). The relative deviances were under 20% in all cases. The results of these tests indicate that the higher the *MC* of the wood, the lower its *CMoE*, which agrees with the literature [11], [12]. The lower *CMoE* of the wood exhibits more plastic properties. Therefore, the higher the *MC* of the wood, the more pliable it becomes. Our specimens with high *MC* and consequently low *CMoE* suffered high, or almost fatal damages during the compression test. For the comparison of the pleated and untreated samples, the pleated sample had 42.9% lower *CMoE* than the untreated sample. Thus, for *CMoE* the pleating has a huge effect on the measurements. This effect is caused by the cell wall deformations during pleating.

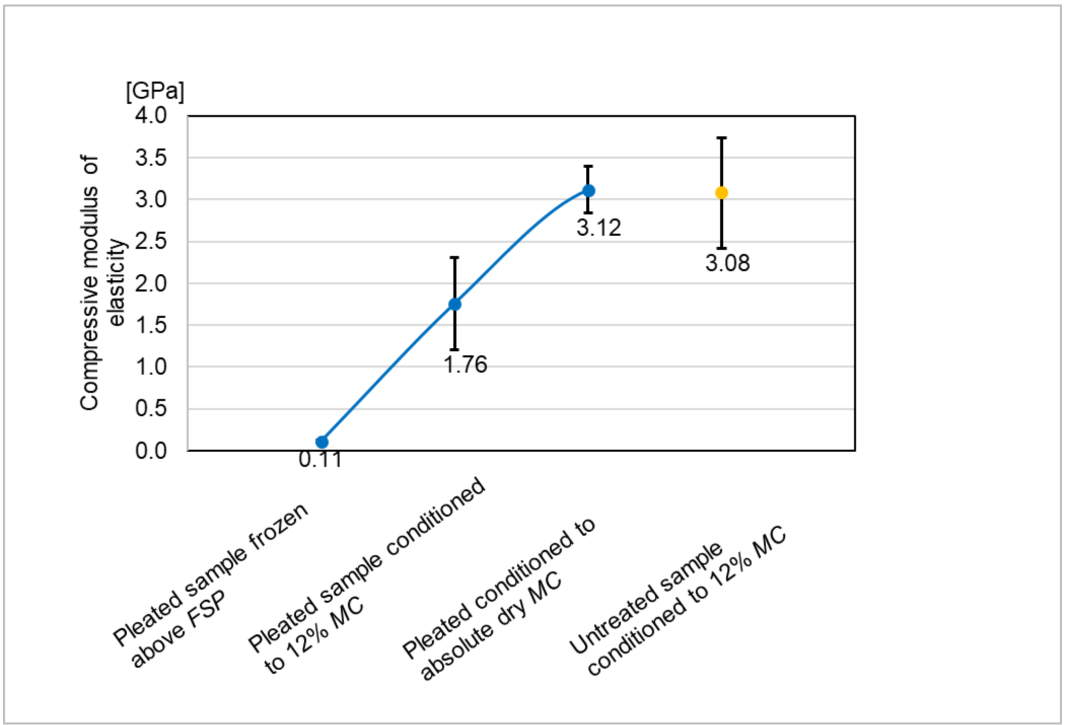

Figure 4. Compressive modulus of elasticity of the samples. Abbreviations: FSP – fibre saturation point; MC – moisture content

4 CONCLUSIONS

During our research, we were able to obtain numerous data from the results of pleated sample frozen above *FSP*, pleated sample conditioned to 12% *MC*, pleated sample conditioned to absolute dry and untreated sample conditioned to 12% (*MC*). The results obtained from pleating demonstrated that the wood of the samples was similar enough to make the post-modification tests comparable. This means that any differences in the compression test results could be attributed to the different *MC*-s. The data obtained from the compression tests showed significant differences. For the untreated sample, the average compressive strength was 55.46 MPa, for the pleated and conditioned to 12% *MC* sample it was 55.55 MPa, for the pleated and conditioned to absolute dry sample it was 93.66 MPa and for the pleated and frozen sample was 40.94 MPa. The higher the moisture content in the wood, the less load it could withstand, but its plasticity increases inversely. These changes between the samples are caused by the lignin and hemicellulose in the wood, as they behave more plastic in the presence of water. The compressive modulus of elasticity for the samples were 3.08 GPa, 1.76 GPa, 3.12 GPa and only 0.11 GPa, respectively. During compression tests, the specimens with higher *MC* typically suffered greater damage however, the samples, with lower *MC* have not shown similarly. For comparison of the pleated and untreated samples, the pleated sample had a 42.9% lower compression modulus of elasticity than the untreated group. That means that pleating has a huge effect on wood. This effect is mostly caused by the cell wall deformations during pleating. In summary, our research has shown that pleating significantly reduces the compression modulus of elasticity of wood, thereby improving its plastic properties and that moisture changes significantly affect the mechanical properties of treated wood.

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