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Advancing Timber for the Future Built Environment

TEMPERATURE-DEPENDENT BENDING MECHANICAL PROPERTIES OF DENSIFIED WOOD

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ABSTRACT: There is interest in using densified low-density softwoods in construction; however, doubts persist due to a lack of knowledge about densified wood at high temperatures. This study investigated the temperature-dependent mechanical properties of thermo-hydro-mechanical (THM) densified Scots pine. Four-point bending and short-term creep tests were conducted on both untreated and densified wood specimens across temperatures ranging from 25 °C to 175 °C. The general trend was a decrease in both MOE and MOR with increasing temperature for both untreated and densified wood. However, the results demonstrate that THM densification significantly enhances the modulus of elasticity (MOE) and modulus of rupture (MOR) across all temperatures, with densified wood retaining superior mechanical properties even at high-temperature conditions. Digital image correlation (DIC) analysis revealed different failure modes: untreated wood exhibited ductile behaviour characterised by progressive damage, whereas densified wood experienced brittle shear failure. Furthermore, the creep tests indicated that densified specimens have approximately 50% lower creep compliance at 150 °C, suggesting improved stability under thermal stress. These findings highlight the potential of THM densification to enhance the fire safety and structural integrity of timber by maintaining load-bearing capacity at elevated temperatures.

KEYWORDS: Bending behaviour; Fire safety; Densification; THM treatment; Scots pine

1 – INTRODUCTION

Thermo-hydro-mechanical (THM) densification has been proven to enhance the mechanical properties of wood significantly, although its application in construction is still restricted [1]. This limitation is partly due to concerns regarding its set-recovery behaviour, which could diminish the improvement in mechanical properties, and a lack of comprehensive knowledge about its fire performance, e.g. behaviour under elevated temperatures. The combustibility of wood is a major challenge when it is used as a construction material [2]. In Europe, fire safety for timber constructions is evaluated primarily based on "reaction to fire" and "fire resistance" according to (EN 13501-1) [3] and EN 13501-2 [4], respectively. When exposed to temperatures above approximately 300 °C, the wood surface thermally degrades into a charred, zero-strength layer, while the affected interior regions experience a progressive loss in mechanical properties due to temperature increase depending on the depth from the surface. According to Eurocode 5, the tension, shear, and compression strengths (parallel to the grain) of wood decline to approximately 65%, 40%, and 25% of their original values, respectively, when the temperature rises from 50 °C to 100 °C [5]. Consequently, designers typically use the reduced cross-section method to estimate the remaining load-bearing capacity and fire resistance [6]. Moreover, ongoing heat penetration may further weaken structural integrity during the cooling phase of a fire [7]. Understanding the temperature-dependent degradation of strength and stiffness is critical for assessing both in-fire and post-fire performance. Notably, the potential for densified wood to retain higher mechanical properties at elevated temperatures could enhance the residual load-

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bearing capacity, thereby affording additional time for evacuation, rescue, and firefighting [8].

The objective of the study was to determine how heating in an open system influence the MOE and MOR of densified wood and relate the results to corresponding un-densified wood.

2 – MATERIAL AND METHOD

2.1 MATERIAL

Straight-grained, defect-free specimens with dimensions of 200 mm (longitudinal) × 20 mm (radial) × 20 mm (tangential) were prepared from kiln-dried Scots pine (*Pinus sylvestris* L.) sapwood. The specimens were randomly assigned to an untreated reference group (R) and a group for further densification, i.e. the densified group (D). Each group was divided into subgroups for static bending tests at constant elevated temperatures of 25, 75, 125, and 175 °C (n = 6) and a short-term creep test at 150 °C (n = 5).

2.2 WOOD DENSIFICATION

Before treatment, the specimens were conditioned at 20 °C and 65% relative humidity (RH) for two weeks. An open-system hydraulic hot-press (Langzauner "Perfect" LZT-UK-30-L, Lambrechten, Austria) was used for the THM densification. The specimens were compressed in the radial direction from 20 to 10 mm in the following stages: (I) the hot press was pre-heated to 170 °C, (II) the specimens were placed in the press, and a pressure of 4 MPa was applied for 3 minutes, (III) the temperature of the press was raised to 200 °C and kept for 2 minutes, and (IV) the press was cooled to 60 °C with the specimens remaining under compression for 5 minutes. Before the bending test and creep test, all specimens were dried at 60 °C and 10% RH for 72 hours. This drying regime resulted in a wood moisture content of 2%, thereby excluding the influence of moisture variations on the bending-test result. The specimens were sawn in dry conditions to dimensions of 200 mm (longitudinal) × 10 mm (radial) × 15 mm (tangential).

2.3 STASTIC BENDING TEST

The four-point bending test based on the EN 408 standard was evaluated by using a universal testing machine (Zwick UTM Z100, Zwick GmbH & Co. KG, Ulm, Germany) with a 100 kN load cell [9]. A climate chamber around the test region was used to regulate the temperature. The specimens were heated to the temperature (25, 75, 125, or 175°C) before loading by placing them in a preheated climate chamber, along with additional matched specimens wired with three thermocouples at the middle depth to establish when the core of the specimens reached the target temperature (Figure 1). The bending test started 5 minutes after the target temperature was reached. The specimens were loaded in the radial direction. The tests were conducted under quasi-static loads at a speed of 5 mm/min, and the MOE values were specified within the range of 10% to 30% of the maximum load. In addition to load and cross-head displacement recordings directly from the universal testing machine, a digital image correlation (DIC) system (Aramis adjustable, GOM GmbH, Germany) was used for measuring the surface strains on one side of the specimen during the bending process (Figure 1) at 25 °C. DIC enabled the study of the effect of treatment on strain development and the identification of failure modes. The distinction between the different failure modes was based on a visual inspection of the tested specimens and a comparison made with the obtained strain profiles through DIC.

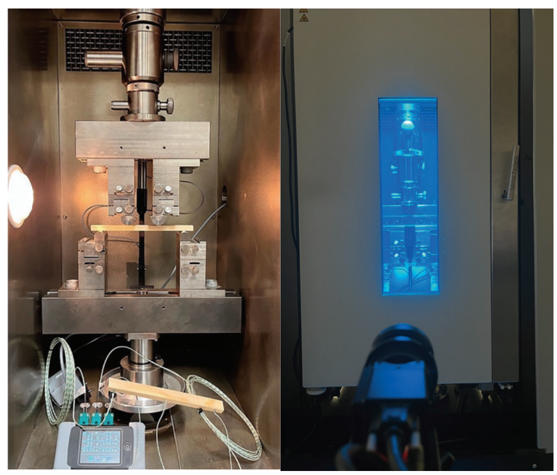


Figure 1. Test setup for four-point bending test at elevated temperature.

2.4 SHORT-TERM CREEP TEST

The creep test was conducted using a custom Multistation testing machine (KAPPA, Zwick GmbH & Co. KG, Ulm, Germany), which can accommodate five specimens simultaneously. The specimens were loaded in a three-point bending test with an applied stress level of 35% of the mean MOR value for each group at 25°C. In this case, relatively large loads were applied to induce significant deformation, and the oven temperatures were controlled to avoid the combustion of the specimens. Each test was run for 120 minutes at 150 °C. An extensometer recorded the mid-span vertical deflection.

To facilitate comparison, the creep is expressed as the total creep compliance $D_t(t)$, creep compliance $D_c(t)$ and initial compliance D_i were calculated according to Eqs. (1), (2).

$$D(t) = \frac{4bd^3}{Fl^3}\ \delta \qquad (1)$$

where b is the width (mm) of the specimens, d is the thickness (mm) of the specimens, F is the applied load (N), l is the span (mm) between supports, δ is the deflection (mm) at time t, and

$$D_t(t) = D_c(t) + D_i \qquad (2)$$

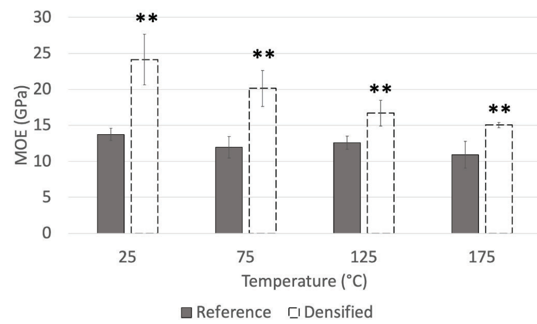
where D_i is the initial compliance after the loading reaches the applied stress target.

2.5 ANALYSIS

The effects of THM densification on bending performance at each temperature level were analysed using a one-way analysis of variance (ANOVA) test and Dunnett's method, as determined by statistical analysis software JMP (SAS Institute Inc., Cary, NC, USA), with a significance level of $p < 0.05$.

3 – RESULTS

After densification, a 50% compression ratio was successfully achieved; therefore, the density of the pine increased from 513 kg/m³ to 1012 kg/m³. As shown in Figure 2, densification significantly enhanced both the MOE and the MOR of Scots pine across all tested temperatures. Figure 3 presents the Eurocode 5 reduction factor k, which quantifies the retention ratio of mechanical properties after thermal exposure [5]. It can be seen that the MOE reduction factor for densified wood declined more steeply than that of untreated wood at equivalent elevated temperatures. Despite this sharper decline, the MOE of densified wood remained substantially higher than untreated wood at every temperature level. Remarkably, densified wood at 175 °C exhibited higher MOE values than untreated wood at ambient conditions of 25 °C. On the other hand, the MOR of both untreated reference and densified wood generally decreased in a similar manner with increasing temperature; however, the MOR of densified wood was always higher than that of untreated reference wood at the same treatment temperature (Figure 2b). The MOR of densified wood at 125 °C was equivalent to that of the untreated reference wood at 25 °C.



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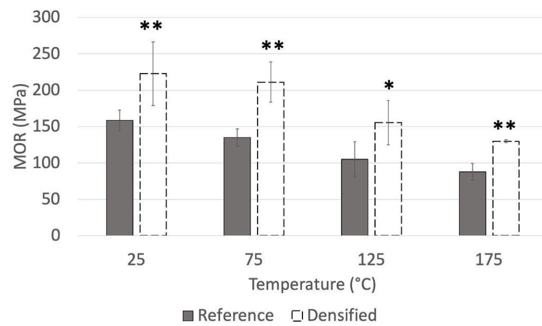
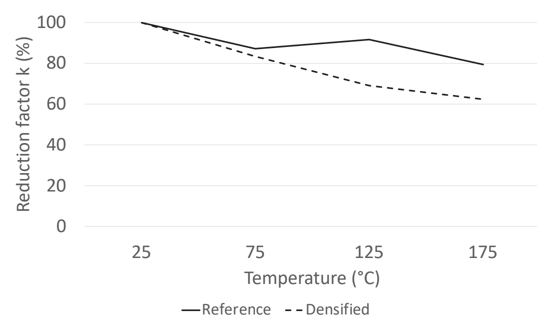


(b)

Figure 2. Temperature-dependent bending performance with standard deviations for the tested temperatures: (a) MOE and (b) MOR.

Data in parentheses, standard deviation. Asterisks denote the significant level of densification on MOE and MOR at each temperature level (* is $p < 0.05$, ** is $p < 0.01$).



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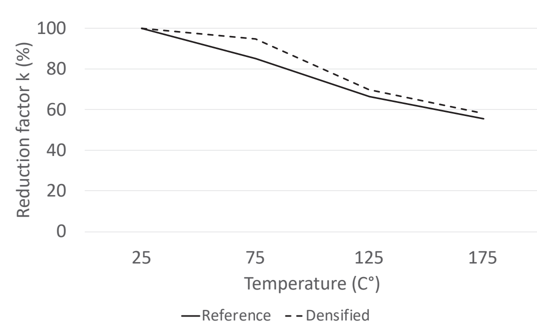

(b)

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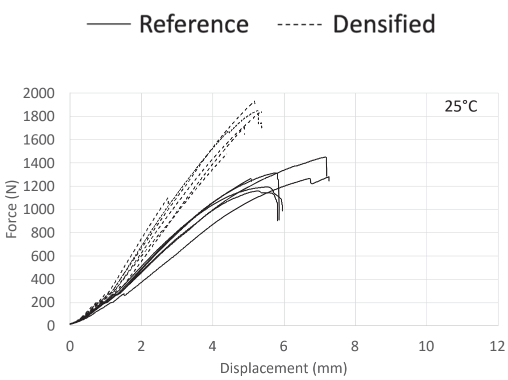
Figure 3. Temperature-dependent reduction factor k for bending performance: (a) MOE and (b) MOR.

Figure 4 show the load-displacement curves of the specimens at different temperatures. For the untreated reference specimens, the bending force increased in a nearly linear manner during the elastic phase, followed by a nonlinear progression through the plastic zone until reaching peak force. Subsequently, untreated specimens predominantly exhibited ductile post-peak behaviour, characterised by gradual deformation and progressive microstructural damage. In contrast, densified specimens demonstrated brittle fracture behaviour, marked by an abrupt decline in bending force immediately after attaining maximum load.



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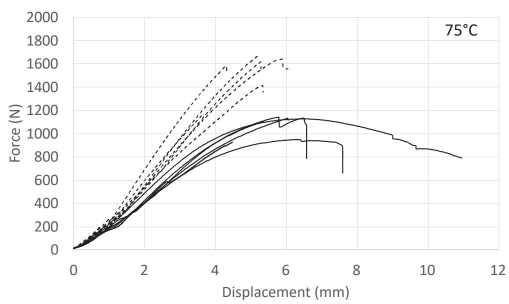

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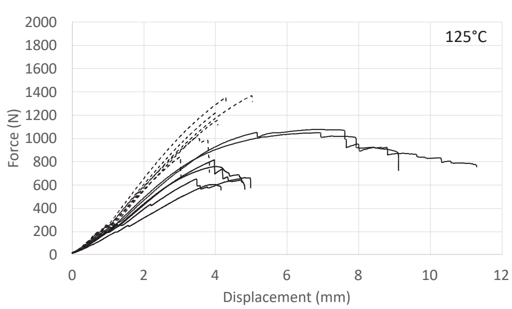

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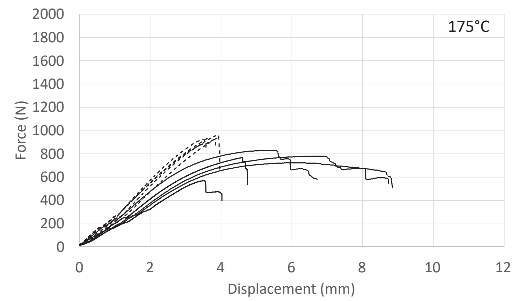

(d)

Figure 4. Bending load-displacement curves of untreated reference and densified wood under different temperatures: (a) 25 °C, (b) 75 °C, (c) 125 °C, and (d) 175 °C.

The DIC strain fields of untreated and densified wood at maximum load align with the failure behaviour, as shown in Figure 4. In Figure 5a, untreated reference specimens exhibit the expected strain distribution under bending, characterised by compressive strain at the top region and tensile strain at the bottom. On the tensile side of untreated wood, strain in the stress concentration zone was released as cracks propagated, followed by the emergence of a new stress concentration point at the crack tip. Consequently, fracture in untreated wood during bending primarily occurs when the tensile load on the tensile side exceeds the material's ultimate strength. In contrast, densified wood demonstrated concentrated shear strain at mid-depth when the load force reached its maximum value (Figure 6b). This observation suggests that the tensile strength of densified wood is significantly enhanced by THM densification, rendering the outer fibres less susceptible to failure. Instead, the shear strength of the mid-layer—which exhibits less pronounced improvement from densification—becomes the critical factor governing failure. Ultimately, sliding between wood fibres parallel to the grain direction leads to horizontal shear failure in densified wood, consistent with its brittle fracture behaviour.

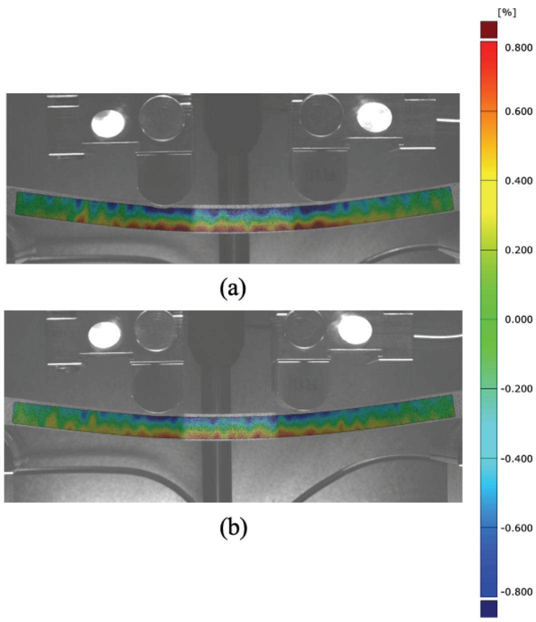

Figure 5. Longitudinal strain field at specimens when reaching maximum load at 25 °C: (a) untreated reference and (b) densified specimens.

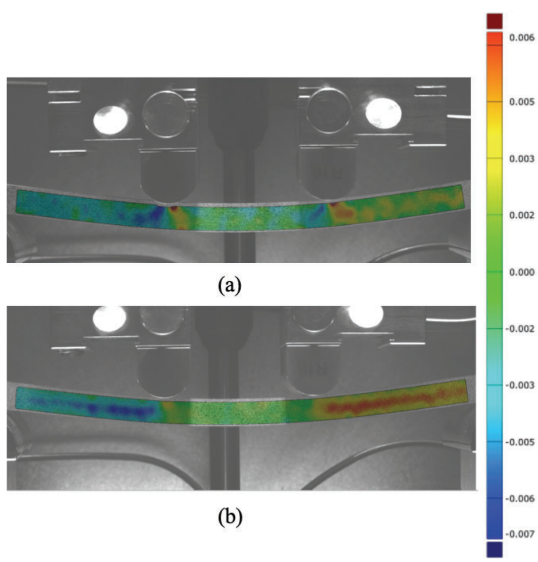

Figure 6. Shear strain field of samples when reaching maximum load at 25 °C: (a) untreated reference and (b) densified specimens.

The creep compliance of both the untreated reference and densified specimens exhibited a rapid initial increase during the first 30 minutes, followed by a gradual decrease over time (Figure 7). At the end of the test, the creep compliance of the untreated R group was 0.31 GPa^{-1}, while the densified groups demonstrated a value reduced by approximately 50%. It was noted that although none of the specimens reached the tertiary creep stage, where the deformation rapidly increases and leads to failure of the material, the creep compliance at 150 °C for 2 hours is close to the value measured at 20 °C for 14 days [10]. Higher exposure temperature and longer exposure time may result in further reduction of structural stability and finally lead to rupture [11]. Consequently, future work will focus on finding the critical ambient temperature and stress thresholds that result in wood rupture, with the aim of improving the fire-safety design in timber construction. Additionally, a comprehensive investigation into the fire performance of densified wood is currently underway, encompassing its reaction-to-fire behaviour and mechanical properties under thermal stress across varied densification parameters. Furthermore, the compatibility of densified wood with fire-retardant coatings and impregnation treatments will be systematically explored.

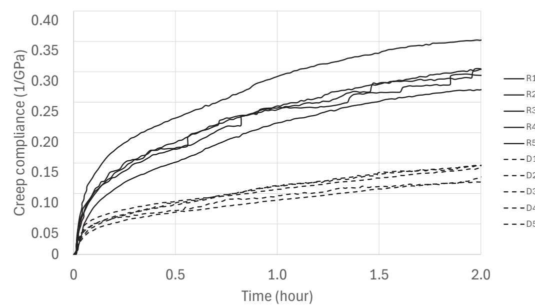

Figure 7. Average creep compliance of untreated and treated wood at 150°C for 120 min. R is the reference group without any treatment; D is the densified group

4 – CONCLUSION

THM densification markedly improves the bending performance and reduces creep deformation of Scots pine under elevated temperatures, though the MOE and MOR are decreasing at elevated temperature. Densified wood consistently demonstrated higher MOE and MOR values compared to untreated specimens, even at temperatures as high as 175 °C. Densification also induced a distinct failure mode transition, shifting from ductile tensile fracture to brittle shear failure. The significantly lower creep compliance observed in densified wood further underscores its ability to maintain structural integrity under prolonged thermal stress. These outcomes suggest that THM densification can play a crucial role in enhancing the fire safety and load-bearing capacity in timber construction.

5 – Acknowledge

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6 – REFERENCE

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