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Creep Properties of Densified Wood in Bending

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Abstract: Thermo-hydro-mechanical (THM)-densified timber is rarely used in construction, although its mechanical properties are in many cases excellent. The main reason for its rare use is set-recovery, which reduces the degree of densification over time so that the mechanical properties deteriorate. Our knowledge of the long-term creep of densified timber is insufficient and a full understanding of its long-term behaviour is still lacking. The purpose of this study was to examine the behaviour under long-term loading of Scots pine sapwood densified in an open system at 170–200 °C. The influence of the THM densification process on the creep properties was studied on (1) unmodified specimens, (2) THM-densified specimens, (3) THM-densified specimens that had been further thermally treated, and (4) low-molecular-weight phenol-formaldehyde resin-impregnated and THM-densified specimens. All specimens were loaded at 20 ± 2 °C and 65 ± 5% relative humidity for 14 days under 3-point bending at 35% of the short-term ultimate load, and the bending deformation was registered. The THM densification doubled the density, causing a significant increase in the modulus of rupture but no change in the modulus of elasticity, and reduced the equilibrium moisture content and creep compliance. Post-thermal modification and resin impregnation improved the dimensional stability and further reduced the creep compliance in bending. The results demonstrate that THM densification combined with resin-impregnation or thermal modification reduces the creep of Scots pine timber under a long-term bending load in a constant climate.

Keywords: thermo-hydro-mechanical densification; Scots pine; creep compliance; thermal modification; resin impregnation

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1. Introduction

Timber has become an increasingly popular building material for commercial, medium and high-rise buildings worldwide due to the general concern regarding the environment and climate change. For timber to be competitive with other construction materials, wood material must be attractive from both a technical and an economic and environmental perspective. Most engineered timber construction elements such as cross-laminated timber (CLT) and glued-laminated timber (GLT) are manufactured from low-density softwoods (typically 300–600 kg m^{-3}) like Norway spruce and Scots pine. These low-density woods have, however, a limited capacity to support heavy loads, and the load-bearing span is limited due to the large deformations under load. Densification is a process to considerably improve the mechanical properties of low-density woods and make them more attractive as a raw material in timber construction elements, for example.

It is well known that there is a strong correlation between many important timber properties and the density, and densification, i.e., the transversal compression of wood, is a method of increasing the density and improving the properties primarily of low-density timber species [1]. In most cases, densification involves a combination of heat, moisture and pressure, i.e., thermo-hydro-mechanical (THM) densification, to deform the wood cells

without fracturing the cell walls, leading to a reduction in the volume of voids within the cells. This means that the maximum bulk density achievable through densification is close to the density of the wood's cell wall, which is about 1500 kg m^{-3} [2]. The increase in hardness, modulus of elasticity (MOE) and modulus of rupture (MOR) in bending usually matches the increase in density achieved during densification [3–5].

During THM densification, the main wood components, except cellulose, become plastic and deform when the wood is under the combined influence of moisture, high temperature and mechanical compression. The semicrystalline cellulose macromolecules are, however, elastically deformed, and elastic strain energy is then stored in the helical semicrystalline microfibrils. The deformation is temporarily fixed by two phenomena: (1) the transfer of lignin from a rubbery state to a glassy state when the wood is cooled to below the glass-transition temperature, and (2) the formation of hydrogen bonds between cellulose and hemicellulose during drying. When the densified wood is again exposed to moisture and heat, the lignin is softened and hydrogen bonds between cellulose and hemicellulose are broken and combined with water molecules. As a result, densified wood cells tend to recover to their original shape and the improvement in properties resulting from densification is lost—a phenomenon known as set-recovery [6,7].

There are three basic ways to avoid set-recovery: (1) to make the cell wall hydrophobic to prevent the wood from being re-softened by the absorption of moisture, (2) to create covalent crosslinks between the wood constituents during densification, and (3) to release the elastic stresses stored inside the microfibrils [8,9]. In practice, steaming wood before or after densification is widely used to prevent the densified wood from recovering to its original shape due to stress relaxation, the degradation of hygroscopic hemicellulose or the breaking of crosslinks between adjacent cellulose molecules [7,10,11]. Other ways to reduce set-recovery are to impregnate the wood with a low molecular-weight resin that acts as a plasticizer before densification, and after curing, locks the wood in its densified shape [12] by modification with ionic liquids [13] or by mechanical locking [14].

With the successful elimination of set-recovery, densification creates the potential for the use of low-density wood in load-bearing structures. Timber used in construction (whether it is in its natural state or not), in engineered wood products or that is modified in some way, will be exposed to long-term loading and will thereby exhibit creep deformation and, in extreme circumstances, lead to early failure of the structure or at least give a negative impact on the serviceability during its service life. With insufficient knowledge of the long-term loading behaviour limits, however, the use of densified wood in timber construction may involve a potential safety risk [15,16].

Wood is a viscoelastic material, i.e., its behaviour under load is time-dependent, showing the characteristics of both elastic and viscous materials. The total creep behaviour can be divided into three main stages, as shown in Figure 1: (1) primary creep, which increases rapidly and then slows down progressively with time; (2) secondary creep, which is almost zero; and (3) tertiary creep where the deformation increases rapidly to failure [17]. Whether or not the tertiary stage occurs in a loaded timber element depends on the stress level (σ). In order to guarantee that the deformation never reaches the tertiary stage resulting in wood failure, Eurocode 5 (CEN 2004) specifies a stress limit (σ_{lim}), which depends on the climate and on the duration of the load [18].

Like all polymeric materials, wood exhibits a complex viscoelastic behaviour depending on the structure, temperature and moisture content (MC), and it is extremely anisotropic [20,21]. In general, the creep behaviour in wood can be divided into two categories that are dependent on the ambient temperature (T) and relative humidity (RH): viscoelastic creep and mechano-sorptive creep [22].

Viscoelastic creep is a deformation beyond the elastic recoverable deformation and arises when wood that is kept at a constant MC in the green state or at an equilibrium MC (EMC) below fibre saturation is instantly loaded to a constant stress level. Viscoelastic creep may occur as an effect of a change in temperature during loading while the MC is kept constant. Mechano-sorptive creep occurs as a consequence of a change in the MC of the

material. When wood is under constant load and the RH cycles from wet to dry, the creep deformation also follows a cyclic pattern, a phenomenon called mechano-sportive creep. Unlike viscoelastic creep, which is time-dependent, the mechano-sportive component of the total creep is directly related to the rate of change and to the range of the change in MC. The accumulative deformation as a result of RH cycles is considerably greater than that of a constant RH, at a given stress level, and mechano-sportive creep can result in premature failure at a low stress level [23].

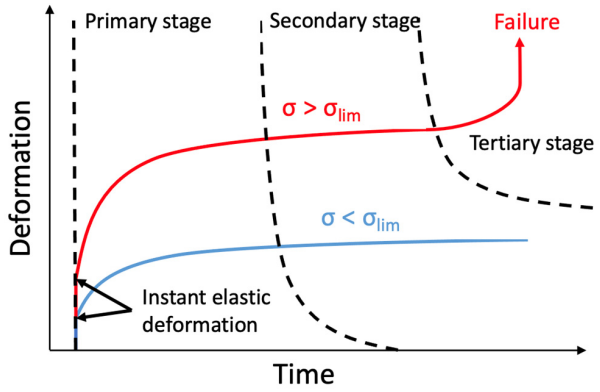


Figure 1. Creep deformation of timber under load. σ = applied load stress, σ_{lim} = ultimate stress limit [19].

Under conditions of moderate loading, constant temperature and constant MC, the time-dependent characteristics of wood can be measured in static (creep, stress relaxation) and dynamic tests. To characterise the linear viscoelastic behaviour of wood, creep and stress relaxation tests are generally preferred to dynamic tests. In static tests, the creep and relaxation functions are obtained explicitly on a time scale, whereas dynamic tests give a complex function related to the frequency. It is not always possible to convert complex dynamic functions to static creep or relaxation functions, but within the limits of linear viscoelasticity, the results obtained from these three methods are mathematically related [24].

Water acts as a natural plasticizer for wood, where the replacement of hydrogen bonds within the amorphous cellulose and hemicellulose increases the movability of the cell-wall constituents. Several studies have reported that viscoelastic creep compliance increases when the MC of wood increases [25–27]. Hering and Niemz [26] studied the viscoelastic creep of European beech timber loaded in bending to 25% of its ultimate strength at different MCs (8, 15 and 23%), and showed that the viscoelastic creep compliance increased by about 8 times when the MC increased from the lowest to the highest tested MC.

The temperature of the wood material affects the viscoelastic creep behaviour both directly and indirectly. With increasing temperature, the thermal action weakens the inter- and intra-molecular interactions such as hydrogen and Van der Waals forces between the main wood components and makes the macromolecular more flexible [28]. Engelund and Salmén [29] showed that the creep deformation of Norway spruce at constant MC increased when the temperature was raised from 10–45 °C. The influence of temperature on the creep becomes more apparent when the glass-transition temperature (Tg) of wood is passed [30]. The Tg of wood is related to the proportions of the main wood components and their MC. The softening of cellulose is limited due to its crystalline and hydrophobic nature, however, and the strong secondary forces between the molecules of crystalline cellulose raise the Tg above the temperature where wood begins to show severe thermal degradation. Because of the branched, highly crosslinked and hydrophobic molecular structure of lignin, its Tg is still above 80 °C when wood reaches the fibre-saturation point. In contrast, the amorphous cellulose and hemicelluloses are hydrophilic, and their Tg can be as low as 20 °C when the MC is high [31].

Because of the natural orthotropic structure of wood, the viscoelastic creep behaviour is also highly dependent on the loading direction, the loading mode and the stress level. The creep of timber when it is loaded perpendicular to the fibre direction can be several times greater than when it is loaded parallel to the fibres, but due to the existence of wood rays, the creep in the radial direction is less than that in the tangential direction. Shear loading results in greater creep than the creep in compression, tension or bending [32]. The ultimate stress level also has a significant effect on the creep level. Roszyk and Kaboorani [27,33] found that wood showed a linear viscoelastic behaviour in bending at stress levels up to 45% of its ultimate strength. Because the creep behaviour of wood is strongly dependent on the MC, Eurocode 5 (CEN 2004) takes into consideration the ambient climate by using the concept of "service class". The standard provides different strength reduction factors (k_{mod}) and different creep coefficients (k_{def}) at different service classes to estimate the load-bearing capacity and total deformation during the structural life. The service class is defined as the temperature and RH of the material in service [18]. For modified timber, the safety factors may differ from those of unmodified timber, but this is not yet well understood.

The objective of the present study was to examine the behaviour of THM densified Scots pine sapwood under long-term loading at a constant climate (Service Class 1 of Eurocode 5). The effects of resin impregnation prior to the THM treatment and thermal modification after the THM densification have also been examined.

2. Materials and Methods

2.1. Specimen Description

Kiln-dried Scots pine (*Pinus sylvestris* L.) sapwood with an MC of 9.4% and an average density of 480 kg m^{-3} (at ≈12% MC) was used. Sixty straight-grained, knot-and defect-free specimens 200 mm (longitudinal) × 20 mm (radial) × 20 mm (tangential) in size were prepared from a single piece of sawn timber. The specimens were randomly distributed into four different groups: (1) reference (R), (2) densified (D), (3) resin-impregnated and densified (RI-D) and, (4) densified and thereafter thermally modified (D-TM), as shown in Figure 2. Each group was divided into sub-groups of five replicates for set-recovery, three-point bending, and creep tests (Table 1).

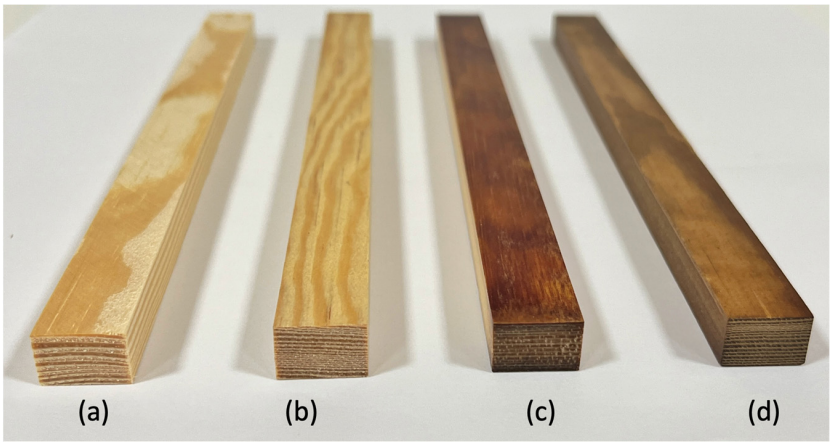


Figure 2. Specimens in the four groups: (**a**) reference without any treatment, (**b**) densified, (**c**) resin-impregnated and densified, and (**d**) densified and thereafter thermally modified.

Table 1. Test groups and numbers of specimens in each group.

Title 1	Set-Recovery	Three-Point Bending Short-Term Test	Three-Point Bending Creep Test
Reference (R)	5	5	5
Densified (D)	5	5	5
Resin-impregnated and densified (RI-D)	5	5	5
Densified and thereafter thermally modified (D-TM)	5	5	5

2.2. Wood Modification

An open-system hydraulic hot-press (Langzauner "Perfect" LZT-UK-30-L, Lambrechten, Austria) equipped with a water-cooling system was used for the THM densification of groups D, RI-D and D-TM. The specimens were compressed in the radial direction from 20 to 10 mm in thickness (50% target compression ratio). A metal stop with a height of 10 mm determined the endpoint. The THM densification included the following stages: (a) the upper and lower platens of the hot press were pre-heated to ≈170 °C, (b) the specimens were placed in the press, and a pressure of 4 MPa was applied in the radial direction with a closing speed of 3 mm s^{-1}, (c) the pressing conditions were held for 3 min after the press platen reached the metal stop, (d) the temperature of the upper and lower platens was raised to ≈200 °C and kept at this temperature for 2 min, and (e) the upper and lower platens were cooled to ≈60 °C with the specimens remaining under compression. The press was then opened, and the specimen dimensions were measured immediately (Figure 3).

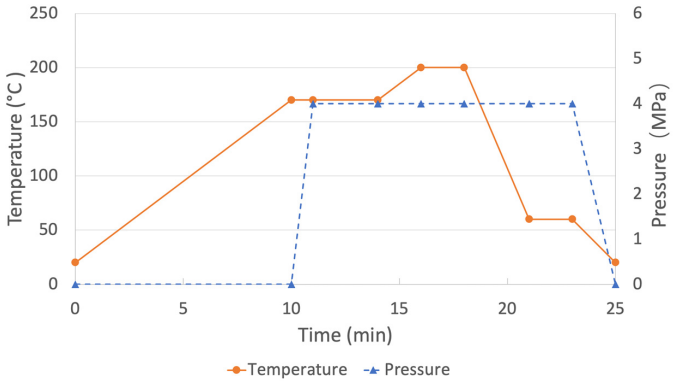


Figure 3. Schedule of thermo-hydro-mechanical (THM) treatment. Closing speed 3 mm s^{-1}.

An aqueous, low-molecular-weight phenol-formaldehyde (PF) resin was used for the impregnation process of group RI-D, supplied by Metadynea Austria GmbH (Krems an der Donau, Austria). A 30% solids content solution was prepared with distilled water. During the impregnation, the wood specimens were submerged in the solution and vacuum impregnated at 0.001 bar for 30 min. The specimens were then dried under indoor conditions for 12 h and afterwards at ≈60 °C in an oven for 24 h.

The thermal modification was carried out for group D-TM in a non-pressurized chamber, heated with a 4 kW electric resistance and a 1.4 bar steam generator following the schedule shown in Figure 4. The process was divided into three stages: (a) the temperature was progressively raised from room temperature (≈20 °C) to ≈200 °C (dry-bulb temperature) for 8 h, (b) the temperature was held at 200 °C for 2 h (thermal-modification stage), and (c) the chamber was cooled down to a temperature of ≈100 °C, and the specimens were removed after the chamber had reached room temperature.

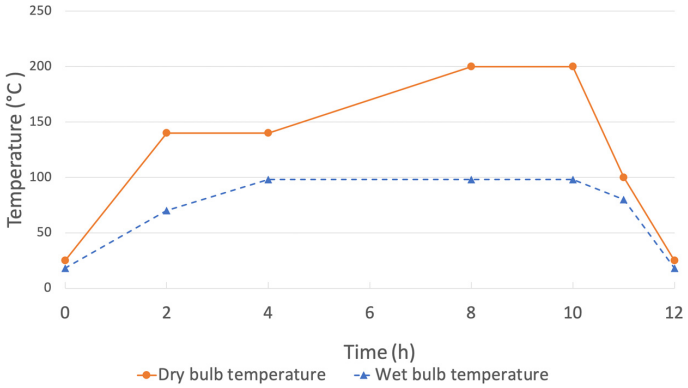


Figure 4. Schedule of thermal modification.

The specimens in all four groups were conditioned at 20 ± 2 °C and 65 ± 5% RH for 2 weeks, and then sawn to final dimensions of 200 mm (longitudinal) × 10 mm (radial) × 15 mm (tangential) before the physical tests were carried out.

2.3. Set-Recovery Test

Before densification, after press opening, and after conditioning at 20 ± 2 °C and 65 ± 5% RH for 2 weeks, the dimensions of the specimens were measured by a digital caliper with a precision of ±0.03 mm, and volume (V) was calculated. The mass (M) of each specimen was also measured on a balance at the same time. The density (ρ) was calculated as Equation (1).

$$\rho = \frac{M}{V} \tag{1}$$

The specimens with a dimension of 200 mm (longitudinal) × 10 mm (radial) × 15 mm (tangential) were kept in a convection oven at a constant temperature of ≈103 °C for 24 h, and the dimension in the densification direction (the radial direction) was measured. The specimens were then immersed in water (≈20 °C) for 24 h followed by oven-drying at ≈103 °C for 24 h. This wet–dry cycle was repeated twice. After each cycle, the specimens were weighed and the dimension in the radial direction was measured at three locations (5, 150 and 195 mm) in the length direction of the specimens with a digital calliper with a precision of ±0.03 mm. The water uptake (W) and the set-recovery (SR) were calculated as Equations (2) and (3).

$$W = \frac{M_1 - M_0}{M_0} \tag{2}$$

where M_1 is the mass after being immersed in water for 24 h, and M_0 is the oven-dry mass, and

$$SR = \frac{T_0' - T_d}{T_0 - T_d} \tag{3}$$

where T_0' is the oven-dry thickness after the wet-dry cycles, T_d is the actual thickness after densification and T_0 is the initial oven-dry thickness before densification.

2.4. Three-Point Bending Short-Term Test

The three-point bending test based on EN 408 (CEN 2012) [34] was carried out using a universal machine Zwick/Roell UTM Z100 (Zwick GmbH & Co. KG, Ulm, Germany) with a 100 kN load cell to determine the modulus of elasticity (*MOE*) and modulus of rupture (*MOR*). The loading span was set to 160 mm, and the speed of loading was controlled by a displacement rate of 5 mm min^{-1}. The specimens were loaded in the radial direction. *MOE* and *MOR* values were calculated as Equations (4) and (5).

$$MOE = \frac{Pl^3}{4bd^3\,\Delta} \tag{4}$$

$$MOR = \frac{3F_{max}l}{2bd^2} \quad (5)$$

where P is the load difference (N) in the elasticity zone, l is the supporting span (mm), b is the width (mm) of the specimens, d is the thickness (mm) of the specimens, Δ is the deflection (mm) at mid-length below the proportion of deflection limit, and F_{max} is the maximum load (N) when the specimen breaks.

2.5. Three-Point Bending Creep Test

The creep test was carried out in a custom KAPPA Multistation testing machine (Zwick GmbH & Co. KG, Ulm, Germany), able to accommodate five specimens simultaneously. The specimens were loaded as in the three-point bending with an applied stress level at 35% of the mean MOR value for each group given in Table 2. Each test was run for 14 days at 20 ± 2 °C and 65 ± 5% RH, in accordance with Service Class 1 as defined in Eurocode 5 (CEN 2004). The mid-span vertical deflection was recorded by an extensometer.

Table 2. Physical and flexural properties of untreated and treated specimens.

	After Press Opening	After 2 Weeks Conditioning at 20 ± 2 °C and 65 ± 5% RH						
Group	**Thickness (mm)**	**Thickness (mm)**	**Density (kg m^{-3})**	**EMC (%)**	**MOE (GPa)**	**MOR (MPa)**	**Water Uptake (%)**	**Set-Recovery (%)**
R	/	/	480 (±0.04) C	9.4 (±1.6) C	12.4 (±1.9) B	101.5 (±10.4) C	47.5 (±11.7) C	/
D	9.85 (±0.05) A	10.67 (±0.18) A	940 (±0.04) B	7.0 (±0.7) B	14.0 (±3.4) AB	166.8 (±25.9) AB	81.1 (±21.3) A	72.3 (±4.1) C
RI-D	9.83 (±0.05) A	10.09 (±0.06) B	980 (±0.04) A	5.2 (±0.7) A	19.4 (±4.1) A	212.7 (±38.5) A	23.8 (±14.5) B	24.7 (±11.3) A
D-TM	9.83 (±0.03) A	10.12 (±0.12) B	910 (±0.03) B	6.2 (±0.6) AB	17.0 (±4.3) AB	157.4 (±40.4) B	35.3 (±14.0) B	6.5 (±1.2) B

R is the reference group without any treatment; D is the densified group; RI-D is the resin-impregnated and densified group; D-TM is the densified and thereafter thermally modified group. Values with different letters behind indicate a statistically significant difference (Scheff's post-test, $p < 0.05$).

To facilitate comparison, the creep is expressed as the total creep compliance $D_t(t)$, creep compliance $D_c(t)$, initial compliance D_i, and the relative creep compliance $R_c(t)$, which were calculated according to Equations (6)–(8), respectively.

$$D(t) = \frac{4bd^3}{Fl^3}\,\delta \quad (6)$$

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 support, δ is the deflection (mm) at time t,

$$D_t(t) = D_c(t) + D_i \quad (7)$$

where D_i is the initial compliance after the loading reached the applied stress target, and

$$R_c(t) = \frac{D_c(t)}{D_i} \quad (8)$$

where $D_c(t)$ is the creep compliance at time t and D_i is the initial creep compliance after the load reaches the applied stress target.

The anti-creep efficiency (ACE) is a value to quantify the ability of a specific modification to reduce the creep deformation [35], calculated as Equation (9).

$$ACE = \frac{DJ_u - DJ_t}{DJ_u} \quad (9)$$

2.6. Statistical Analysis

All the results are expressed as mean values with standard deviations. The normality and homogeneity of the data's variance were verified by the Shapiro–Wilk and the Levene's tests, respectively. The results were satisfactory for the application of parametric tests.

Therefore, a comparison between the results was performed by one-way analysis of variance (ANOVA) with Scheff's post-test at a significance level of 5%.

3. Results and Discussion

3.1. Physical and Flexural Properties

Table 2 shows the physical and flexural properties of the different groups of specimens. After press opening, the dimensions of the densified specimens in the compression direction (thickness direction) were slightly less than the end-stop limit (10 mm) due to shrinkage, which means that the 50% compression ratio was successfully achieved. The density of the RI-D group was slightly higher than that of the D group due to the mass gain during resin impregnation, and the D-TM group had a slightly lower density due to thermal degradation of the wood substance.

As shown in Table 2, after conditioning at 20 ± 2 °C and 65 ± 5% RH for 2 weeks, a small set-recovery was recorded for the modified specimens (D, RI-D, and D-TM). All the modified groups had a statistically significant lower EMC 20 ± 2 °C and 65 ± 5% RH compared with the untreated R group, especially the EMC of the RI-D group, which was only 5.2%. The mean MOE was slightly improved by densification, but there was no significant difference between the D and R groups. Nevertheless, the resin impregnation combined with densification (RI-D) gave a considerable increase in the MOE. The densification leads to an improvement by about 64% on the MOR. When combining resin-impregnation with densification, RI-D showed further increases on the MOR due to the impregnation induced higher density and permanent swelling of the cell wall [36,37]. The thermal modification, however, slightly reduced the densification-induced MOR improvement, presumably because the non-crystalline cellulose, hemicellulose and extractives were thermally degraded [7,10].

The resin impregnation and thermal modification reduced the water uptake and set-recovery considerably compared to the D group. The high plasticizing effect of the PF resin on the wood cell wall [12] can effectively decrease the inner stresses generated during densification and therefore prevent set-recovery if specimens are exposed to moisture, and the cured resin in the cell wall can provide excellent anti-swelling efficiency when exposed to a varying climate [36]. The post-thermal modification weakens the connection between the microfibrils and lignin and leads to hydrolysis of the hemicelluloses and, therefore, allows internal stresses to relax [38].

3.2. Three-Point Bending Creep

The creep compliance of Scots pine under constant climate was significantly changed by the densification (Table 3). The initial creep compliance of the modified groups (D, RI-D, and D-TM) was about half that of the untreated R-group, which can be attributed to the EMC reduction. There was no significant difference in the relative creep between the untreated R groups and the modified groups (D, RI-D, and D-TM) after 14 days.

Table 3. Result of bending creep test.

Groups	D_i (GPa^{-1})	D_c (14d) (GPa^{-1})	R_c (14d) (%)	ACE (14d) (%)
R	1.02 (±0.11) A	0.36 (±0.07) A	34.88 (±3.69) AB	/
D	0.57 (±0.11) B	0.21 (±0.04) B	36.88 (±3.71) A	41 A
RI-D	0.50 (±0.11) B	0.16 (±0.02) B	33.45 (±4.17) AB	54 A
D-TM	0.65 (±0.08) B	0.16 (±0.05) B	25.43 (±8.48) A	54 A

R is the reference group without any treatment; D is the densified group; RI-D is the resin-impregnated and densified group; D-TM is the densified and thereafter thermally modified group. D_i is the creep compliance after loading achieved target applied stress and called initial compliance; D_c (14d) is the creep compliance except for initial compliance at 14 days; R_c (14d) is relative creep at day 14; ACE (14d) is Anti-creep efficiency at day 14. Values with different letters behind indicate a statistically significant difference (Scheff's post-test, $p < 0.05$).

The creep compliance of all the groups showed a rapid increase in the first 2 days and followed by a gradual slowing down with time (Figure 5). At the end of the test, the

creep compliance of the untreated R group was 0.36 GPa^{-1}, whereas that of the modified groups (D, RI-D, and D-TM) was only about half this value. Compared to the untreated R group, the creep compliance of all the modified groups (D, RI-D, and D-TM) was reduced by 40–55% after 14 days, which means that the densification reduced the creep deformation and that both resin impregnation and thermal modification enhanced this effect. This result agrees with a previous study of the viscoelastic properties of densified wood using dynamic mechanical analysis, which showed a lower creep compliance of densified wood under controlled RH [39]. None of the specimens reached the tertiary creep stage, where the deformation rapidly increases and leads to failure of the material.

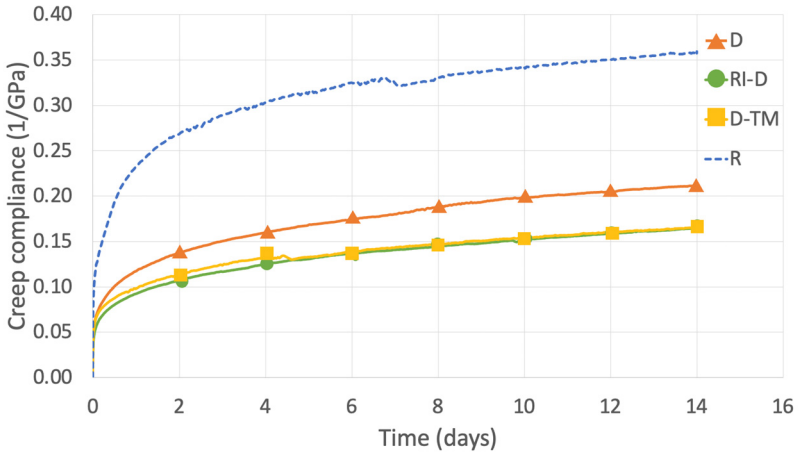


Figure 5. Average creep compliance of untreated and treated wood for 14 days. R is the reference group without any treatment; D is the densified group; RI-D is the resin-impregnated and densified group; D-TM is the densified and thereafter thermally modified group.

It was assumed that the modification-induced change in the chemical components and the change in hygroscopicity contribute to the creep compliance reduction. It has been reported that the crystallinity increases during densification due to the hydrolysis and depolymerization of amorphous wood components [40–42]. Since the change in cell wall crystallinity contributes to about 60% variation in the total creep deformation in a constant environment [43], the densification-induced crystallinity increase may also reduce the creep deformation. The lower viscoelastic creep at low EMC is because water is a natural plasticizer for wood. Compared with wood at a low EMC, there are more water molecules in wood with a high EMC and these break the hydrogen bonds within the amorphous components. As a result, there is more free space for the movement of polymer molecules, the intermolecular bonding energy is weakened and finally the slipping between molecular chains and the loosening of cell wall structure increases the creep compliance [27,44].

Impregnation with a thermosetting resin enhances the bonding between wood microfibres and therefore reduces the creep compliance [45,46]. Xiang [47] reported that thermal modification can also significantly increase the crystallinity, crystalline thickness, and crystalline length of wood, which reinforces the arrangement of cellulose molecular chains and therefore reduces creep compliance. In addition, the thermal modification induced condensation polymerization of lignin also increases the creep resistance [48].

4. Conclusions

THM densification leads to a significant increase in density and therefore increases the bending strength but not the MOE of Scots pine sapwood. The THM densified wood showed a reduced time-dependent creep under long-term constant load in a stable environment compared to that of untreated wood. The initial compliance and creep compliance of THM densified wood after 14 days of loading was reduced by 40% compared to that of untreated wood. In summary, THM densification shows the potential to increase the use of low-density wood in construction for long-term loading.

Both resin impregnation and thermal modification considerably reduced the set-recovery of the THM densified wood. In addition, resin impregnation and thermal modification combined with densification can maintain and enhance the densification-induced property improvement. The EMC is an essential factor influencing the creep behaviour of wood, and since the treatments applied in this study lead to a lower EMC of modified wood (group D, group RI-D, and group D-TM), this could be the primary reason for the reduced creep compliance. A future study should therefore focus on how the modification-induced change in EMC affects the bending creep behaviour.

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