Cabral et al. Journal of Wood Science (2022) 68:20
https://doi.org/10.1186/s10086-022-02028-3

Journal of Wood Science

REVIEW ARTICLE

Open Access

Densification of timber: a review on the process, material properties, and application

John Paul Cabral*, Bidur Kafle, Mahbube Subhani, Johannes Reiner and Mahmud Ashraf

Abstract

Timber densification is a process that has been around since the early 1900s and is predominantly used to enhance the structural properties of timber. The process of densification provides the timber with a greater mechanical strength, hardness, abrasion resistance, and dimensional stability in comparison to its virgin counterparts. It alters the cellular structure of the timber through compression, chemical impregnation, or the combination of the two. This in turn closes the voids of the timber or fills the porosity of the cell wall structure, increasing the density of the timber and, therefore, changing its properties. Several processes are reported in literature which produce densified timber, considering the effect of various parameters, such as the compression ratio, and the temperature on the mechanical properties of the densified timber. This paper presents an overview of the current processes of timber densification and its corresponding effects. The material properties of densified timber, applications, and possible future directions are also explored, as the potential of this innovative material is still not fully realised.

Keywords: Chemical densification, Compression, Densification, Densified timber, Mechanical densification, Sustainability

Introduction

Over the years, the push for timber and forest management has been extensive to meet the demand for environmental sustainability. In addition, shortage of structural timber is apparent, particularly in Australia, where bushfires have ravaged the plantations in late 2019 and early 2020. As a result, the timber industries are pressed on creating products that utilise the forest more efficiently. Timber is considered as a natural renewable resource that is widely used as a building construction material due to its inherent high strength-to-weight ratio that is comparable to other commonly used structural materials, such as concrete and steel. Specific trees are used for their natural properties, meaning that they are selected based on their performance and strength [1]. This natural material comes from different origins, and variations on their mechanical properties due to individualised conditions require timber to be modified and engineered to overcome deficiencies [2]. Sandberg et al. enumerated some of the weaknesses that are targeted by engineering as the following: moisture sensitiveness, low dimensional stability, hardness and wear resistance, low resistance to bio-deterioration against fungi, termites, marine borers, and low resistance to ultraviolet (UV) irradiation [1].

Several mechanical properties, such as strength, hardness, and surface abrasion resistance of timber are correlated with its density. Therefore, timber species with a higher density are often preferred for structural applications, where strength is an important parameter. Considering the positive correlation of density with different mechanical properties, several attempts in increasing the density of timber through modification were made; this process is called densification. Densification is essentially an increase of quality and density of timber by decreasing the voids in the material through different techniques,

*Correspondence: cabralj@deakin.edu.au
School of Engineering, Deakin University, Waurn Ponds, Victoria, Australia

such as compression of the timber, use of heat and steam, impregnation of substances into the lumen, or a combination of all of these [2, 3]. These processes increase the density of timber and eventually enhance the mechanical properties of timber, such as its Modulus of Rupture (MOR), Modulus of Elasticity (MOE), stiffness, and hardness.

The first processes and concepts of densification have been proposed in the early 1900 in the United States when patents were submitted for compressed timber [3]. While early studies primarily focused on different techniques for densification and compression of timber, recent studies are more inclined on the stabilisation of the behaviours of the densified timber. Most of the studies investigated the effects of compression ratio (CR), temperature, pressing time, moisture content (MC), and other parameters to contribute to both the improvement of the densification methodologies and qualities of densified timber. In addition, optimisation through the use of statistical tools were carried out to determine the impact of individual parameters, as well as combinatorial effects on the responses. Both softwood and hardwood species are used for densification and the improved products are used in different types of applications, such as connections, floor and wall systems, and framing. This paper presents a review on the background and types of densification processes with their manufacturing characteristics and limitations. Mechanical properties of densified timber from the reported investigations are critically reviewed.

Characteristics of virgin timber

Material properties of virgin timber

Timber is known to be an anisotropic material because of its cellular structure. It is considered to have three axes of symmetry, namely, the longitudinal, radial, and tangential directions. Directional properties of the timber are generally known as parallel to the grain (longitudinal), and perpendicular to the grain (radial and tangential directions) [4]. These directional fibres affect the properties of timber, where MOE is a good indicator of the variation in strength. Longitudinal direction is observed to have the highest MOE compared to transverse directions [5]. The cellular structure of timber is mainly composed of long slender cells that are oriented parallel to the axis of the stem. These cells are known to have a nearly rectangular shape with hollow centres called lumen [6]. The cellular structure of softwood species differs depending on the age of the timber, with earlywood having a lower density than latewood and, therefore, offer different mechanical properties, as illustrated in Fig. 1. The more compact structure of the latewood in comparison with the earlywood gives it a higher density and, therefore, higher mechanical properties than the latter. Meanwhile, distinct differences in vessel elements or porosity of hardwoods based on their species in conjunction with their growth rate heavily affect the strength of hardwoods.

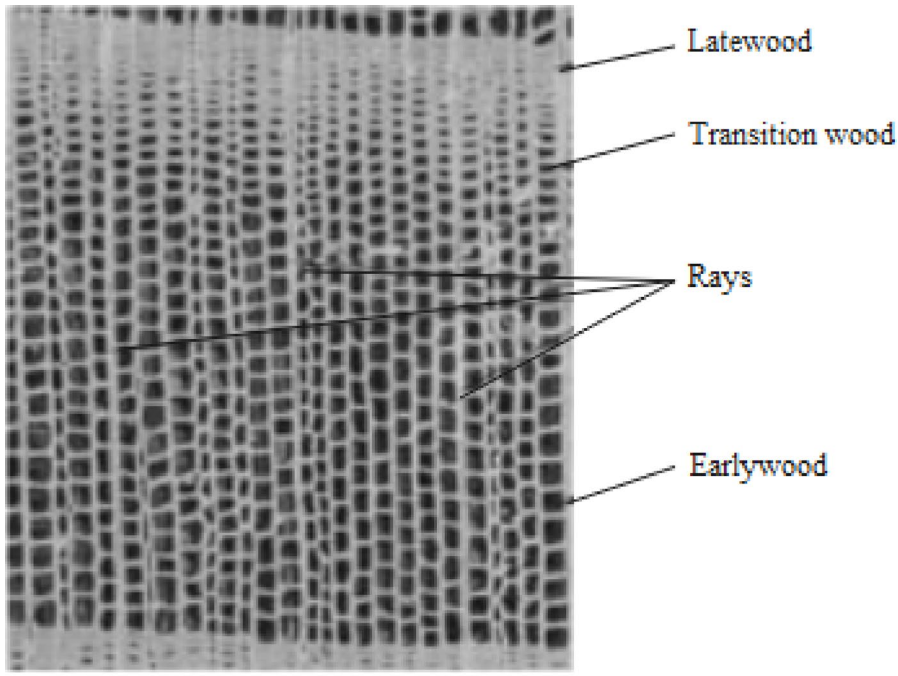
Variations in material properties are also affected by the species of timber, with hardwoods having higher densities, and, therefore, higher strengths. In addition, species variation is also seen depending on the region, where timber is grown. Table 1 shows variations in material properties for green and dry timber for some of the common species.

In addition to the strength of the timber, several other physical properties are influenced by these fibres as well, such as the density, shrinkage, stiffness, colour, fire resistance, termite resistance, electrical resistance, and mechanical damping [8]. Most of these properties are shaped by the cellular structure of the timber, which is made up of cellulose, hemicellulose, and lignin [9].

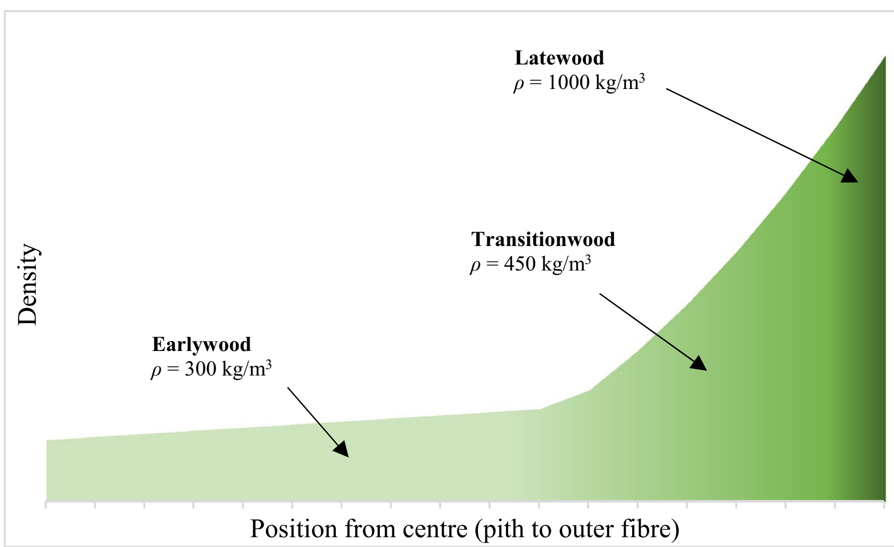
Timber constituents

Timber is essentially a composite structure made up of 'timber constituents' [10]. Figure 2 illustrates the cellular structure of a trunk made with the timber constituents, which are divided into the main macromolecular components, such as cellulose, hemicellulose, and lignin, and the minor low-molecular-weight components, such as extractives and mineral substances. The former is present in all kinds of timber, and the latter differs in type and amount based on the species of the timber. The approximate composition of the cell-wall, varying with species, are 50% cellulose, 25% hemicellulose, 20–25% lignin, and 1–5% of extractives [11].

Cellulose is considered to be the structural basis of all plant cells and one of the most abundant natural substance in the biosphere. It consists of anhydroglucopyranose units and is known to be a linear-polymer glucan with long and linear chains [11, 12]. Cellulose has a high tensile strength due to the covalent bonding present within the cells, and higher rigidity due to the hydrogen bonds that attach cellulose to the surrounding timber constituents [13]. The structure of the hemicellulose is a series of carbohydrate molecules containing the six carbon sugars [13]. As opposed to the long and linear chain of the cellulose, hemicelluloses are branched-chain polymers [14]. Moreover, these structures are different between hardwood and softwoods, wherein softwood hemicelluloses are galactoglucomannan and arabinoglucuronoxylan, and the hardwood hemicellulose is glucuronoxylan [12]. Lignin is known as an adhesive that provides rigidity and compressive strength to the cell wall [12]. The composition of lignin is modelled after three-dimensional phenolic polymers, as opposed to linear or branched carbohydrate chains. The hydrophobic



(a)



(b)

Fig. 1 **a** Cellular structure of timber and **b** density distribution (reproduced from [6])

characteristic of lignin makes the cell walls of the timber water-repellent. In addition, this characteristic partly affects the strength by lessening the effect of water on the hydrogen structure of the timber, as moisture enters the timber structure [13].

These three molecular components have a complex relationship between MC, temperature, and time of loading, changing the interaction between the constituents and, therefore, influences different aspects of the timber, such as its strength, deformation, and softening

Table 1 Species and material properties of timber [7]

Species	Source	Density (kg/m^3)		MOR (MPa)		MOE (GPa)		Maximum Crushing Strength (MPa)	
		Green	Dry	Green	Dry	Green	Dry	Green	Dry
Pine, radiata	New Zealand	930	480	41	76	7.3	9.1	18	41
Pine, radiata	SA, VIC (Australia)	800	500	42	81	8.1	10.0	19	42
Spruce, Sitka	Great Britain		385	34	67	5.9	8.1	16	36
Pine, maritime	Great Britain		480	36	77	6.6	8.9	17	40
Larch, European	Great Britain		545	53	92	7.9	9.9	24	47

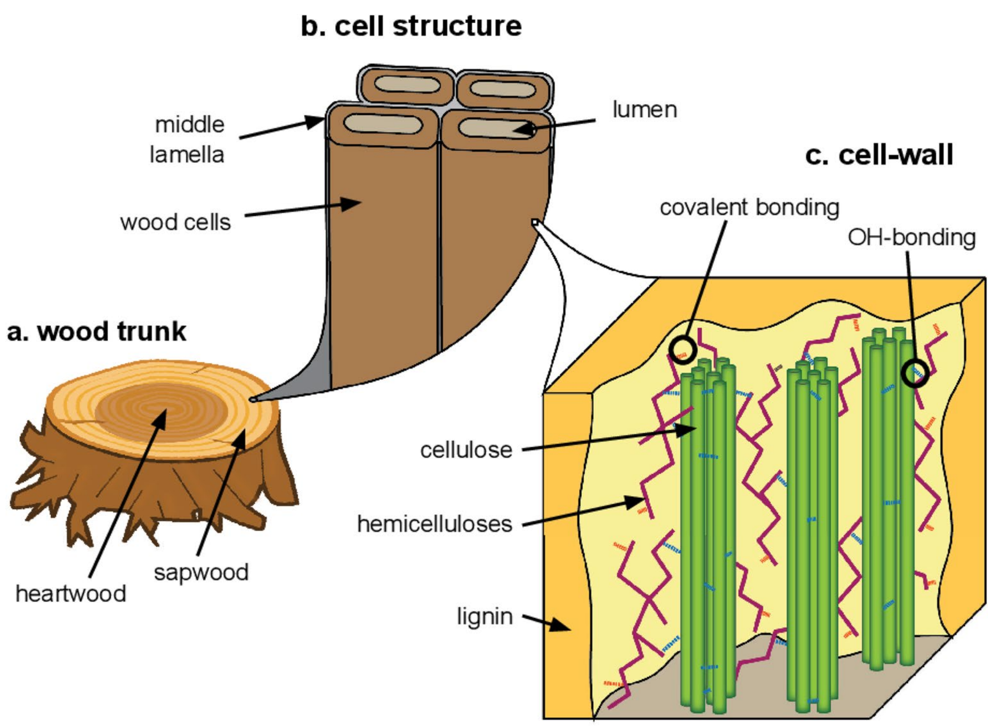


Fig. 2 Cellular structure and timber constituents [10]

behaviour. One of the key characteristic that affects these is the glass transition temperature.

Glass transition temperature

The material characteristic of timber is generally defined as hard and brittle. As timber constituents are hygroscopic to an extent, depending on the temperature and MC of the timber, this description changes [15]. Properties of timber are partly dependent on the three aforementioned timber constituents' glass transition temperature (T_g). The T_g is an approximate temperature at which the material starts to soften. The T_g of the timber depends on the concentrations of the constituents as well as the structural arrangement in the cell-wall. MCs of the cellulose, hemicellulose, and lignin, also act as a softener and influence their respective glass transition temperatures. Data generally show that increasing MC in timber, despite the differences in species, decrease the softening temperature of the timber [15–18]. Figure 3 shows the approximate T_g of timber constituents based on MC [15]. It can be seen that a higher MC yields a lower temperature to reach T_g. This effect however flattens out for lignin and does not go lower than 86 °C. The approximate points of intersection for lignin and hemicellulose are at 12% MC and 97 °C, and for cellulose and lignin the intersection is around 30% MC and 86 °C.

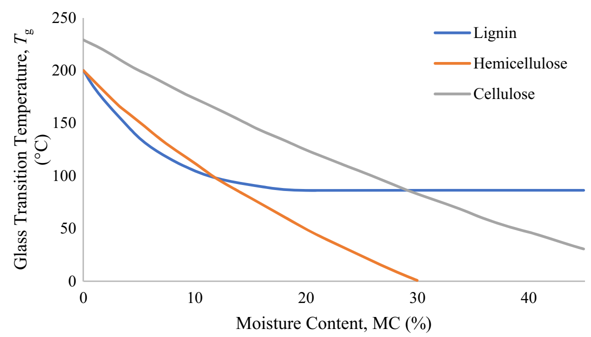


Fig. 3 T_g vs MC of timber constituents (reproduced from [15])

Strength properties, particularly the MOE of timber, are greatly affected by the glass transition temperature. Once timber passes the T_g, its material characteristic changes from glassy to a rubber-elastic state, altering the MOE and softening the substance of the timber. It has also been noted that in order for softened materials to flow, the temperature of timber has to be at approximately 50 °C higher than the T_g [16]. This softening phenomenon is crucial to the densification of timber.

Fundamentals of timber densification

The densification process takes advantage of the viscoelastic behaviour of timber and makes it possible for low-density timber species to be engineered and used competitively, in place of higher density and higher performance timber [3]. Evidently, the process depends on the extent of the collapse of the cellular structure to characterise the final mechanical and physical properties of the timber [19]. This process is not entirely limited to softwoods but can also be used in hardwood species as well to improve their stiffness and strength characteristics.

The anisotropic nature of timber enables the densification process to be accomplished in different directions, either longitudinally, radially, or tangentially. While longitudinal and tangential densification is possible, previous research did not delve deeply into the implications of densification in these directions. Radial densification is the most commonly used process, as the materials used are mainly sapwood boards which have a nearly parallel growth ring pattern to the edges of sawn timber.

Densification typically consists of 6 basic steps and takes advantage of the viscoelastic properties of timber as well as the softening characteristic in relation to the glass transition temperature of the timber constituents, particularly the hemicellulose and the lignin. This highlights the importance of temperature, moisture, and load on the material that enables the timber to be compressed without being crushed. In addition, compression is also a function of other anatomical factors, such as the density before densification, percentage of latewood and earlywood, volume, and the direction of load [3]. Schematic of the basic process of densifying timber is presented in Fig. 4 and described below:

The level of densification applied to a virgin timber using the densification process is called CR and specifies the reduction of thickness of a timber (Eq. 1). Springback (SB) is defined as the thickness recovery of densified timber immediately after release of the compression load and is due to the thermoplastic nature of lignin [20] (Eq. 2). Set-recovery (SR) is also a thickness recovery but after replasticisation of the densified timber during usage

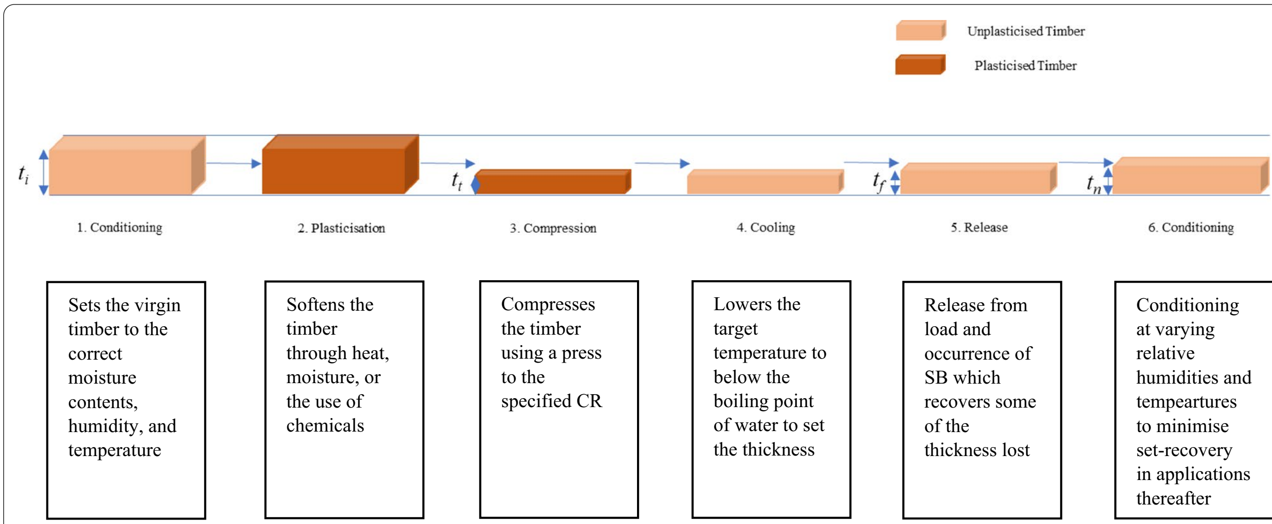


Fig. 4 Schematic showing different stages of densification

or soaking. It is a time-based process that depends on the severity of replasticisation. Therefore, it can last from a few minutes to a few years and is calculated using Eq. 3:

$$\text{Compression Ratio, CR} = \left(\frac{t_i - t_f}{t_i}\right) * 100[\%] \quad (1)$$

$$\text{Spring} - \text{back, SB} = \left[\frac{(t_f - t_t)}{(t_t)}\right] * 100[\%] \quad (2)$$

$$\text{Set} - \text{recovery, SR} = \left[\frac{(t_n - t_f)}{(t_n)}\right] * 100[\%] \quad (3)$$

where t_i is the initial thickness of the virgin timber, t_f is the final thickness taken immediately after the release step, t_t is the target thickness for the compressed timber before release, and t_n is the thickness of the compressed timber after use and replasticisation.

While the densification processes use similar steps in achieving the final product, several differences can be seen in each of the densification methods. Changes in different parameters, tools used, and even added steps are included to improve the strength, SR, processing time and accessibility, and overall usability of the densified timber.

Densification techniques used for timber

Densification of timber can be done through mechanical or chemical processes, such as either compressing the timber and forcefully closing the voids of the timber or filling the porosity of the cell wall structure with chemicals to reduce the voids in solid timber; mechanical and chemical processes can also be combined for densification.

Mechanical densification

Thermo-mechanical (TM) densification

Stabilisation of timber through heating is one of the oldest and simplest ways of increasing its value and use. Early research set the main foundations of the concept of densification using heat to improve dimensional stability, and compression to enhance the density and strength of the timber [21, 22]. TM densification is commonly done using open hot-press, where there is no control over the MC and relative humidity (RH) of the environment, and hence pre-treatment is crucial. Consequently, in the process of densification through heat-stabilisation, timber is pre-heated and conditioned to a MC of 13% which eliminates the risk of damage during the compression stage [23]. This also increases the flow of lignin in the timber which consequently relieves the internal stresses of the timber during compression [20]. Following pre-heating, timber is compressed using a hot-press in temperatures ranging from 130 to 180 °C, and then set and fixated through cooling of the panels to less than the temperature of the boiling point of water before withdrawal of compression. Without this step, significant SB will occur due to the thermoplastic nature of lignin [20]. The resulting product is timber with high density, strength, and dimensional stability.

A range of variables can be considered with the manufacturing of densified timber through heat-stabilisation. Changes in temperature, CR, MC, RH, and time of heating all offer different effects on the densified timber, such as increased hygroscopicity, dimensional stability, durability, surface quality, MOR, MOE, Janka hardness, surface abrasion, and the nail/screw withdrawal strength [20, 24–35].

Thermo-hydro-mechanical (THM) densification

The process of subjecting timber through the effects of temperature, moisture, and mechanical action is called the THM process. Combination of these three effects is utilised to overcome the drawbacks of densification and thermal treatment, such as SR and SB. Stabilisation through the injection of steam before or during the compression stage improves the dimensional stability of the timber through the steam softening of the lignin and hemicellulose matrix and not through degradation of the hemicelluloses. Due to the softened matrix and the microfibrils move, a decline in mechanical properties is minimised and surface hardness is increased while improving the dimensional stability of the densified timber [36]. This process increases the compressibility of timber and reduces the level of stress stored by compression through the promotion of viscous flow of timber substances [37]. Through hemicellulose hydrolysis and elution using moisture and its mechano-sorptive effect, complete fixation can be achieved with increasing temperatures and decreasing times [38–40]. This produces stable timber that is permanently fixated and has improved efficiency, dimensional stability, decreased hygroscopicity, and enhanced density, mechanical properties, and durability over TM Densified timber [36–46]. However, Chen et al. recently proposed that changes in the crystallinity and crystal width of the cellulose explains the possible mechanism underlying shape fixation through steaming [43]. In addition, changes in the mechanical properties through steaming were explained through a slip-cure model, wherein the timber cell wall acquires microfractures in compression, and steaming induces a rearrangement of the crystalline cellulose, setting the compressed shape of the timber [43].

The technique of creating densified timber is similar to heat-stabilisation, however one difference is that steam circulation instead of dry heat during compression is utilised to fixate the deformation of the timber. This requires holes or grooves on the surface of the compression plates. This process also utilises an enclosed system, allowing a strict control of variables such temperature, MC, pressure, and RH inside the closed system [38]. Moreover, the use of moisture in the treatment stages contributes to the hydrolysis of the celluloses and enables stress relaxation to occur in the timber, therefore, increasing the dimensional stability of the timber and the improvement of the aforementioned properties [44].

Viscoelastic thermal compression (VTC)

VTC densification takes advantage of the natural behaviour of the polymers (cellulose, hemicellulose, and lignin) found in timber which are both viscous and elastic. The process of VTC densification involves a continuous apparatus that enables (1) simultaneous heating and conditioning; (2) timber softening through rapid vapour decompression; (3) compression; (4) annealing to promote thermal degradation and relaxation; and (5) cooling and conditioning of the panels. An example of this is patented by Kamke and Sizemore, as shown in Fig. 5 [47].

The viscoelastic polymers of timber can behave either as viscous fluids or as linear elastic solids depending on temperature, duration of exposure and diluent concentration [47]. High temperatures, high MCs, and longer exposure can be associated with timber that exhibit compliance and a rubbery state, while lower temperatures, low MCs, and shorter exposure times produce timber that display a glassy behaviour. Properties of these viscoelastic polymers change when the timber surpasses its T_g, exploiting the mechanosorptive effect of timber. Temperatures exceeding the T_g, combined with inducing rapid vapor decompression and removal of water in the cell wall softens the molecules of the timber and promotes polymer mobility, preventing brittle fractures even with large cross-sectional movement [3]. Through treatment in this transition phase, the resulting material is a densified timber with increased strength, stiffness, and decreased hygroscopicity [47].

Surface densification

Surface densification only affects the first few millimetres of the timber and hence the densification process is quicker than usual [48], resulting in a change in density profile of the densified timber board. Sharing the same principles as heat-stabilisation, surface densification utilises heat to press the first few millimetres of the timber. Early studies have investigated this by continuously using a combination of belt and heated shoes that linearly move. This process sandwiches the panels and cools them down using water-cooled shoes at the end. This subjects the timber to short periods of heat and pressure, followed by a cooling step afterwards [49]. However, the process of surface densification is not limited to this. Different processes, such as the use of linear vibration friction technology (LVFT), VTC, THM, or regular heat-stabilisation with altered compression times have come up in recent years [48, 50–58]. All of which have successfully altered the density profiles of the timber and increased the densities of the surface of the timber. Changes in density profiles have the potential for different applications due to the variation of density peaks and valleys, and since wear and abrasion resistance are mostly density dependent, this type of timber can be used in applications such as flooring, wherein surface hardness and a soft core is required [59, 60].

Chemical densification

The pursuit of dimensional stability and reduction of SR on densified timber has led researchers to explore the use of chemicals to impregnate the timber, improving their mechanical properties. Chemical modification is a process, wherein the polymeric constituents of timber, such as lignin, hemicellulose, or cellulose, go through a chemical reaction with an agent and form a stable covalent

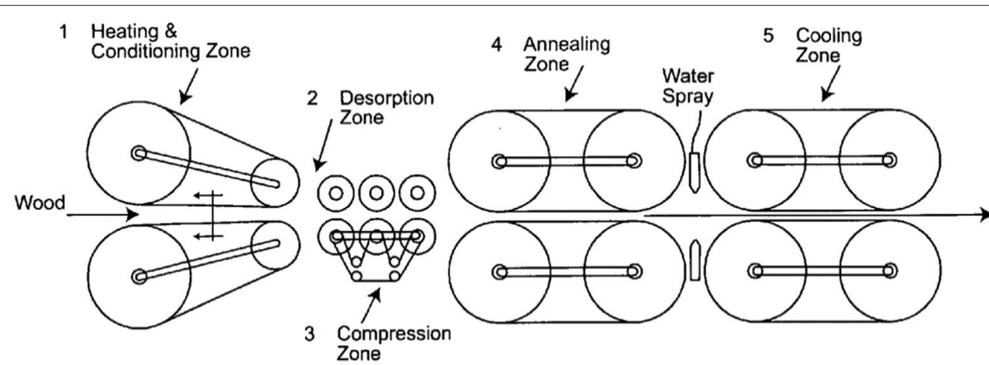


Fig. 5 Continuous VTC densification apparatus [47]

bond between the reagent and the timber constituents [61]. Since the primary use of chemicals in timber is to improve the dimensional stability, overall durability and lifespan of the timber, the combination of impregnation and densification complement each other. Examples of chemicals used are acetic anhydride, phenol-formaldehyde, and melamine-formaldehyde.

Acetic-anhydride

Several catalysts have been explored for acetylation over time. Examples such as zinc chloride, urea–ammonium sulphate, dimethylformamide, sodium acetate, magnesium persulfate, trifluoroacetic acid, boron trifluoride, and γ-rays have been researched; however, recently most acetylation reactions are performed without the use of catalysts. The acetylation process evolved by limiting the amount of acetic anhydride and acetic acid used, and heating up the specimens to 120 °C and 130 °C for solid timber (after soaking in cold anhydride); and for other samples such as fibres, particles chips, veneer and thin solid timber, temperatures of 120 °C–165 °C were applied [62]. Acetic anhydride reacts with the timber constituents and results in the esterification of accessible hydroxyl groups in the cell wall, forming acetic acid. This by-product is then removed from the final product due to its odour. As a result of the acetylation process, the resulting product has high dimensional stability due to the decrease in hygroscopicity, high hardness properties, and increased fungal resistance. A limitation, however, is that no increases in mechanical properties are seen in the acetylation process [62–68].

Phenol-formaldehyde (PF)

The impregnation of timber with the use of PF gives the timber better dimensional stability and resistance to swelling and shrinking, greatly reducing the SB tendencies of the timber when the resin is completely cured. Through penetration of the cell-wall structure and bonding of the active groups in the timber, the resin is able to minimise the swelling and shrinking of the timber structure by filling the capillaries of the timber and blocking the entrance and exit of water without affecting the equilibrium moisture sorption or equilibrium swelling [69]. This treatment also alters timber's plasticity at polymerization temperatures before setting of the resin, providing good compressibility aspects, in addition to dimensional stability through the crosslinking of timber components [70, 71]. The combination of PF treatments and compression improves the density, strength, hardness, combustion performance, and reduced SR of the densified timber [71–74].

Melamine-formaldehyde (MF)

MF is a thermosetting resin which is available in high concentrations (65–75%) and requires dilution due to its high viscosity; the dilution process requires the MF resin to be produced in an etherified form to increase water tolerance and enables the MF resin to penetrate the timber cellular structure [75]. With MF being one of the hardest and stiffest isotropic polymeric materials, substituting PF resins with MF resins in the impregnation of timber has shown potential in improving several properties of timber, such as MOE, hardness, weathering resistance, and dimensional stability [75, 76]. Almost complete fixation of the timber after thermal compression is seen with specimen soaking and boiling under water [75], performing better than THM treatments in soaking cycles and efficiency in production due to the elimination of drying and cooling stages [77, 78].

Summary

Underlying challenges with the existing densification techniques

Despite improved properties of the heat-stabilised densified timber, one of the limitations is the occurrence of SR. This phenomenon is dependent on several factors, such as density, CR, and timber species, wherein a lower density timber and higher CR exhibits higher SR, mainly due to the internal stresses induced in the densification process [54]. The occurrence of SR may be reduced through the increase of compression temperature, and compression time [24, 79–81], but prevention of SR is usually done through thermal modification during the post-treatment stage [82, 83]. The core idea of thermal modification in post-treatment is to heat the timber above temperatures of 150 °C to accelerate chemical reactions in the timber [82]. However, the pursuit of dimensional stability led to reduced mechanical performance. In addition, the appearance of the timber is changed, darkening further as the dimensional stability increases [20].

Improvements required on the process of TM densification led researchers to explore different methods of stabilising the dimensions of timber with changes in MC, along with THM densification. Theoretically, stabilisation of timber happens through thermal degradation of the hemicelluloses in the cell wall [36], which can be overcome by suitable combinations of temperature, moisture, and mechanical action. Although improvements in the properties of densified timber were seen through THM densification, this treatment is limited to small timber samples that are relatively uniform. The requirement of an autoclave or a sealed vessel limits the production to small-scale specimens, similar to VTC densification, in which the thicknesses of the timber samples start within the range of 3–12 mm before compression, due to the need of rapid moisture movement in the system. The MC before VTC densification can be more than the fibre saturation point; however, a MC of 15–30% is preferred [84]. Accordingly, applications are limited to veneers and other engineered wood products (EWP) as well as connection components.

The utilisation of the aforementioned densification techniques resulted in the formation of surface densification. Compared to the traditional densification techniques, surface densification allows a quicker turnaround time for both the densification stages and implements additional treatments for SR, enabling the process to achieve lower energy requirements [50]. Taking advantage of the difference in density profile, surface densified timber can be applied to different scenarios, such as timber flooring and production of single-piece timber composites with high-strength outer layers and low strength cores [85].

The use of chemicals in conjunction with densification gives manufacturers an alternative to the usual TM, THM, and VTC process. Impregnation allows softening of the timber constituents, aiding the densification and compression process, as well as improving different characteristics of densified timber. However, chemicals are often seen negatively due to their composition and cost, as this prevents timber from being reused at the end of their design life, lowering their end-of-life potential. Table 2 presents key features of all the existing densification methods with their relative advantages, requirements, and descriptions.

Future research directions on densification methods

Although the process of densification has been part of the construction industry since the early 1900s, a widely accepted technique of creating densified timber does not exist due to the lack of specific design and quality standards for the densified material specifications. The manufacturing process of densified timber involves several parameters including the type and species of timber, MC, temperature, and CR, and all of these contribute to the final physical and chemical characteristics of the densified timber. The anisotropic nature of timber and variability of timber species add to the complexity of the manufacturing process. In addition, environmental conditions in growth and manufacturing techniques also affect the characteristics of the densified timber. Certain applications of densified timber can require different strength properties as well, highlighting the necessity of optimising manufacturing parameters through the use of standards. It is essential that the development of densification methodologies and testing processes are created to establish guidelines for densified timber. This will also aid in the repeatability of the process and the consistency of end product, i.e., densified timber. Numerical and mathematical models of the properties of different species of timber, based on certain manufacturing variables, can help jump-start the creation of design standards of densified timber. Likewise, a design standard for the application of densified timber in larger structures is essential.

It is important to improve the manufacturing techniques and commercialise the densification procedures. The closest product to densified timber is a resin-impregnated veneer-laminate called Lignostone. Current processes for densifying timber are batch processed and involve several steps that require pre-treating or post-treating the timber as well as compressing the timber over different periods of time. The complexity of the process poses an issue with logistics, as each step of the densification process requires specific machines or conditions to complete. The VTC process proposed an inventive method that consists of a continuous belt and roller that divides the steps into zones and manipulates the viscoelastic behaviour of the material to compress the timber. However, only thin timber components (3–12 mm thick prior to compression) are suited for this process [47]. All of the current densification processes require several steps in creating the densified product, as well as excessive amounts of time in treatment stages, be it in compression, heat, or chemical impregnation, resulting in significant energy consumption and financial costs. Industrial scale densification also requires more intensive control on the MC of the specimens. A study by Welzbacher et al. attempted an industrial scale densification using a thermo-mechanical process and resulted in an explosion during the pressing stage because of the extension of moisture in the specimens [86]. In addition, due to the decrease in volume of the specimens after compression, larger and thicker timber are required initially to use them as structural timber. Usual structural timber thicknesses range from 35 to 45 mm, which would require a thickness of approximately 100 mm before densification to compress to a level in which mechanical properties increase significantly. One way of utilising densified timber is through the creation of laminates and treating the densified timber as veneers, with a similar layup as laminated veneer lumber (LVL), glue-laminated timber (Glulam), or cross-laminated timber (CLT). Further work is required in the industrialisation, improvement on energy consumption and application aspect of densified timber.

Properties of densified timber

Mechanical properties of densified timber have been investigated by researchers over the years, outlining the factors (inherent to timber and manufacturing

Table 2 Summary of densification methods

	Conditioning stage	Pre-heating/pre-treatment stage	Compression stage	Cooling stage	Post-Treatment Stage
TM	MC = 12–13%	Usage of platens or steam	Usage of heated platens Temp = 130 °C–180 °C Pressure < = 14 MPa	Temperature < 100 °C before release	Post-heating (ThermoWood Process)
	No thickness limitation	Open process	Holding time = minutes–hours Open process		Post-steaming
THM	MC = 12%	Usage of saturated steam	Usage of heated platens and steam Temp = 110 °C–200 °C Pressure < = 13 MPa	Temperature = 60 °C	Not required
	No thickness limitation	Enclosed process	Increased steam pressure and temperature as treatment Holding time = minutes–hours	Purging of the steam pressure before release	
VTC	MC = 12%	Conditioning the timber through heat or steam compression such that the glass transition temperature of the timber constituents is reached	Usage of heated platens Temperature = 80 °C–200 °C (varies depending on T_g) Pressure = 2–4 MPa	Temperature < 100 °C before release	Not required
	Virgin Timber Thickness = 3–12 mm	Usage of rapid vapour decompression to induce mechanosorption and to lower the compression modulus of the timber	Annealing Temperature < T_g Holding time = minutes		
CHEMICAL	Follows densification method used	Impregnation using chemicals, such as acetyl anhydride, PF, MF, or other substances	Lower compressing pressures due to softening of timber constituents by impregnation Holding = minutes to hours	Follows densification method used	Not required

parameters) that influence different properties of the engineered timber. Species of timber, as well as different manufacturing techniques affect the properties of the timber including the mechanical strength, hardness and abrasion, and dimensional stability of the densified end product.

Mechanical strength characteristics of densified timber

Tabarsa and Chui studied the effects of hot-pressing on the properties of white spruce (*Picea glauca* (Moench.) Voss) in relation to different CRs and pressing temperatures [25]. Figure 6 presents the effect of temperatures on MOE and MOR obtained from experiments. In general, hot-pressing improved the MOR and MOE of the specimens. It was observed that pressing temperature had a larger effect on MOE and MOR than the CR. MOE and MOR are higher at higher temperatures, mainly due to lower cell wall damage from compression, higher densification, and lower SB of the specimens [25]. The results, in comparison to control specimens, suggest that positive changes in mechanical properties are only realised at CRs higher than 15% and temperatures higher than 100 °C. At temperatures above 100 °C, a thermal softening phenomenon and a loss of amorphous polysaccharides break the intermolecular and intramolecular bonds of the timber [87]. However, contradicting results have been shown that an increase in temperature does not merit higher mechanical properties, and an increase of pressing temperature in the densification process even decreased the timber strength properties [26]. Rather, the CR of the specimens governed the increasing MOE and MOR of the timber [88]. In addition, Ulker et al. suggested that an increase of pressing temperature in the densification process decreased the strength properties of Scots pine [88].

This was further investigated by Anshari et al., as the MOE and shear modulus of densified *sugi* was investigated in different directions of the specimen [30]. Figure 7 presents the results, wherein G is the shear modulus, E is the MOE, and L, R, and T are the longitudinal, radial, and tangential directions, respectively. MOE generally increased with increasing CR, and E_L increased the most significantly; reaching the highest MOE of 32,858 MPa and increasing by 309% from the base. It was observed that the G values in the LT plane showed improvement with increasing CR, gaining approximately 754% at a 70% CR. Contrary results were observed in the LR plane, even decreasing to less than the virgin timber's properties. This is mainly due to the densification occurring in the radial direction. Furthermore, a similar trend was observed by Yoshihara and Tsunematsu, where LR plane shear modulus decreased and the minimum being at 50% CR [41]. It was inferred that the variation of shear modulus is due to the slippage induced at the fracture between planes. MOE values on the other hand, increased in both the L and T directions. Radial MOE was affected negatively, with the exception of the 70% compressed timber, due to the fracture of timber cells during the densification process.

Tanaka et al. investigated the bending and shear strength properties of densified *sugi* adopted as a connector [29]. It was reported that an improvement in both bending and shear strength was seen through the densification process. Yoshihara and Tsunematsu, however, reported that there is no correlation between bending strength and CR [41]. In contrast, compressive strength of densified timber increased with increasing CR and density as mentioned by Pelit and Yorulmaz [34]. Pelit and Yorulmaz investigated the effects of densification on the mechanical properties of thermally pre-treated spruce and poplar timber and found that thermal pretreatments generally had a positive effect on the MOE (up to 200 °C treatment temperature) and a negative effect on the density, Brinell hardness and MOR of timber [34]. The three values decreased by 9%, 28%, and

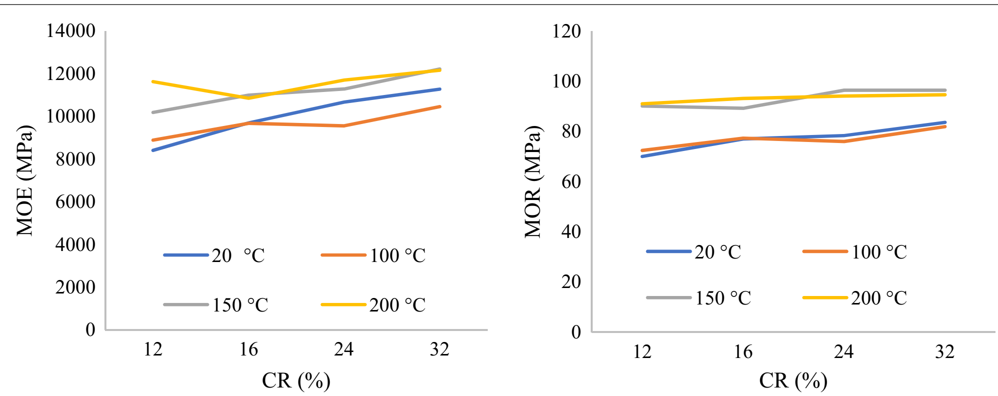


Fig. 6 Results from [25] comparing various pressing temperatures and CR to MOE and MOR

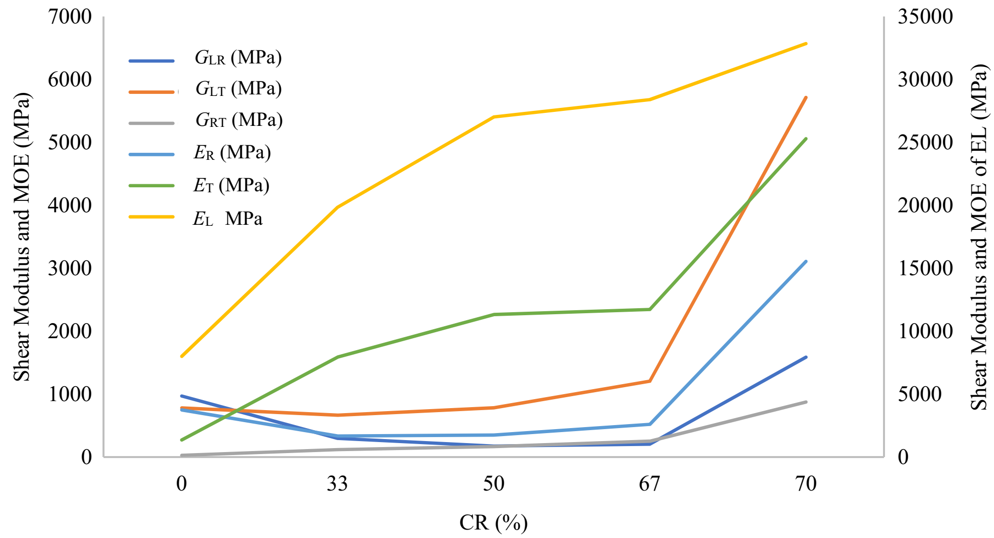


Fig. 7 Results from [30] comparing the MOE and Shear Modulus of different directions and CRs

37%, respectively, at 200 °C with 9 h pre-treatment time. Sözbir et al. also found that both heat treated timber (HTT) and heat treated densified timber (HTD) densities increased until 200 °C [35]. Thermal degradation of the hemicellulose at higher temperatures negatively affected the pre-treated timber at varying rates. Furthermore, a study by Navi and Heger found that temperatures greater than 180 °C led to a reduction in mechanical properties due to the macroscopic cracks in the lignin of the timber [39]. While dry heat usually results in degradation at higher temperatures, steam has a different effect. Kutnar and Kamke investigated the effects of compression of timber in VTC under three different steam conditions [89, 90]. It was established that the condition of the steam environment and the temperature of compression affected the relative density and the strength properties of the timber. Compression under transient conditions at 170 °C produced the highest density and the greatest MOE and MOR of the samples, while compression under superheated steam resulted in a lesser increase of properties in the experiment. THM densification also produce improvements on density, shear strength, and MOE over the earlier forms of densification processes. A large contributing factor to this is the increased plasticisation that occurs in THM processes due to the moisture that is present in the pores, vessels and lumen of the timber [43].

Densification with chemical processes improves the strength properties as well. Shams et al. investigated the deformation behaviour of low molecular weight PF resin-impregnated timber under compression in the radial direction [91]. The process enables the manufacturing of high-strength timber using low pressures. It was reported that at the same pressure, PF resin-impregnated timber has a higher density than untreated timber. At approximately 10 MPa, the PF resin-impregnated timber has a density of 1300 kg/m^3 in comparison to the untreated timber with 850 kg/m^3. It was also observed that the MOE and the bending strength of the timber increased linearly regardless of the PF impregnation. Higher concentrations of PF resin also resulted in higher mechanical properties for the timber [92]. Different parameters used for compressing PF resin-impregnated timber also yielded different results for the MOE and bending strength. Analysing the data reported by Shams and Yano, Fig. 8 shows trends on the changes in various mechanical properties with varying manufacturing parameters [92]. It is seen that resin concentration is linearly and positively correlated with MOE and MOR. This is due to the increase in weight, volume, and density which is the main driver for the increase in mechanical properties. Preheating temperature reduced both the MOE and MOR of the samples as it increased. Lower densities were seen in preheated samples with higher temperature, mainly due to the condensation of the resin, affecting the plasticising effect of the impregnation. In turn, this reduced both the compressibility of the timber as well as the final density of the timber. Pressing temperature has a negligible effect on the mechanical properties at temperatures below 160 °C, however it has a negative effect on MOE and MOR on temperatures from 160 °C and above. While pressing temperature assisted in the plasticisation of the timber, higher temperatures accelerated the condensation of the resin and hindered the

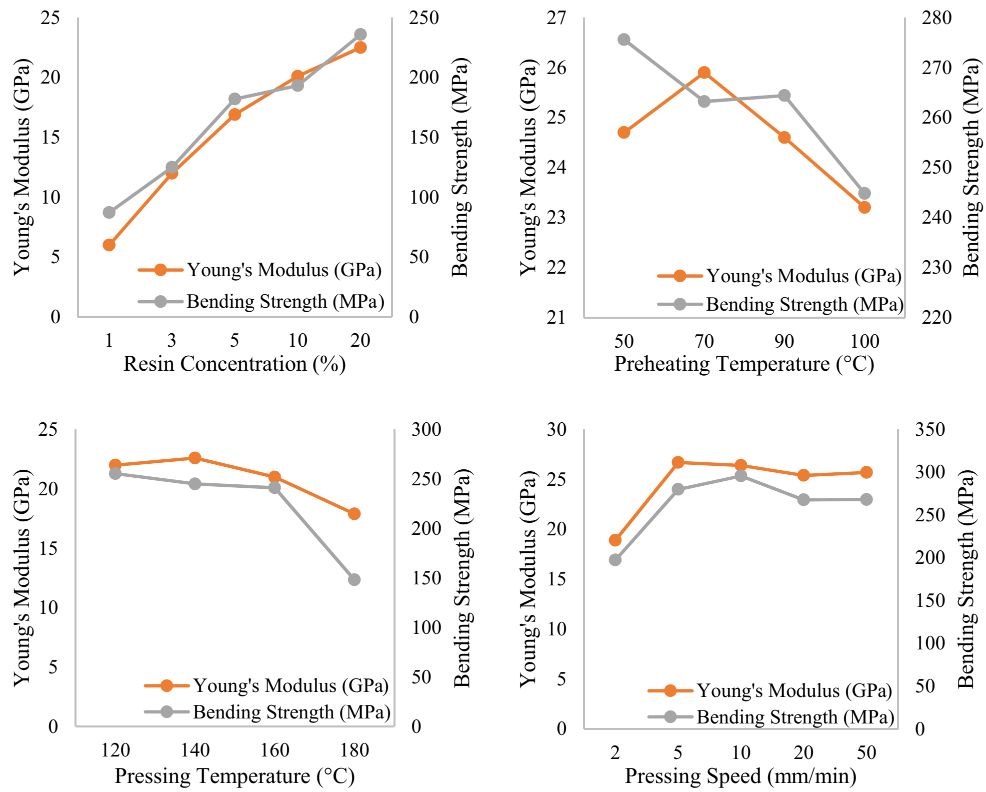


Fig. 8 Analysis of trends observed in the mechanical properties of PF resin impregnated timber with different parameters [92]

compression of the timber. In addition, thermal degradation can be attributed to the lower mechanical properties of the samples. No significant differences were found on the effect on pressing speed, with the exception of the pressing speed of 2 mm/min. This highlights the importance of pre-heating temperature, pressing temperature, and resin concentration on the determination of the optimal parameters for densified timber. Moreover, compressive behaviour and deformation behaviour of PF resin-impregnated timber is species dependent, and softwoods collapse more easily at lower pressures than hardwoods due to their simple structure [93]. It was established that low density timber species, such as softwoods have an advantage in creating high-strength timber with PF resin-impregnation, yielding better results than hardwood species.

The use of a mixture of sodium hydroxide and sodium sulphite can be used in densification as well. Song et al. investigated the effects of high-temperature compression in combination with a chemical treatment of sodium hydroxide and sodium sulphite to manufacture densified timber [94]. Density, compression strengths in all three directions as well as the ultimate tensile strength were reported to have increased.

Key mechanical strength properties of densified timber with different species, methods, and parameters have been summarised in Table 3 and 4.

Stress–strain behaviour

Most studies on materials to increase their strength results in a decrease in ductility, which produces high strengths materials showing brittle behaviour during failure. Bouhala et al. reported compressive stress–strain behaviour of densified and undensified timber after investigating the application of compressed timber on adhesive free timber structures [95].

Finite element simulations were performed based on a user-defined constitutive law with multi-yield surface plasticity to describe the behaviour of the timber material. From the analysis, a comparison between the stress–strain curves of densified and undensified timber, as shown in Fig. 9, were obtained through experimental and numerical means. Compressive stress–strain diagrams exhibit different behaviours of densified timber when compared to undensified timber. Failures of the specimens tested in radial direction are brittle with a sharp load drop once the strength limit is reached. Compression in the tangential

Table 3 Summary of MOE and MOR of densified timber from various densification method research

References	Species	Testing standard	Densification method	Parameters tested	Density (% change)	MOE/MOR (% change)
[40]	*Populus tomentosa* (Chinese white poplar)	GB/T 1936.1–2009	THM	CR (50–75%)	82.93–217.07%	30.00–120.00%/44.00–93.33%
[41]	*Picea sitchensis* Carr. (Sitka spruce)	ASTM D143-94 JIS Z2101-94	THM	CR (33–67%)	33.33–77.78%	78.57–114.29%/− 11.11–11.11%
[84]	*Populus deltoides* × *Populus trichocarpa* (Hybrid poplar)	Not reported	VTC	CR (63–132%)	61.88–139.27%	37.93–128.74%/32.89–102.63%
[89]	*Populus deltoides* × *Populus trichocarpa* (Hybrid poplar)	Not reported	VTC	Steam Temperature (150–170 °C)	87.67–228.73%	51.24–314.60%/31.85–260.31%
[91]	*Cryptomerica japonica* D. Don (Sugi)	Not reported	PF Densification	Pressure (0–10 MPa)	105.88–311.77%	11.11–200.00%/44.44–211.11%
[92]	*Cryptomerica japonica* D. Don (Sugi)	Not reported	PF Densification	Resin Concentration (1–20%), Pressing Temperature (120–180 °C), Preheat Temperature (50–100 °C), Pressing Speed (2–50 mm/min)	41.18–264.71%	Not reported/ Not reported
[93]	*Paraserianthes falkata* (Albizia)	Not reported	PF Densification	Species	200%	233.33%/250%
	Cryptomeria japonica (Sugi)				140%	162.5%/128.57%
	Pseudotsuga douglasii (Douglas fir)				63.64%	78.57%/40%
	Ulmus sp. (Elm)				40%	28.57%/5.88%
	Betula maximowicziana (Birch)				21.43%	13.33%/− 6.67%

GB/T Chinese GB Standards, *ASTM* American Society for Testing and Materials, *JIS* Japanese Industrial Standards

Table 4 Summary of MOE and MOR of densified timber from various TM densification research

References	Species	Testing standard	Densification method	Parameters tested	Density (% change)	MOE/MOR (% change)
[25]	*Picea glauca* (Moench.) Voss. (White spruce)	Not reported	TM	CR (12–32%), Pressing Temperature (20–200 °C)	Not reported	− 5.52 to 36.63%/− 4.11 to 32.05%
[27]	*Cryptomerica japonica* D. Don (Sugi)	Not reported	TM	CR (33–50%), Pressing Temperature (140–200 °C)	36.36–87.88%	17.98–60.67%/9.85–54.85%
[29]	*Cryptomerica japonica* D. Don (Sugi)	JIS Z2101	TM	CR (30–70%), Direction	28.57–251.43%	16.67–166.67%/50.00–183.33%
[30]	*Cryptomerica japonica* D. Don (Sugi)	Not reported	TM	CR (33–70%), MC (6–16%)	33.33–300%	148.3–310.73%/Not reported
[33]	*Pterocarya fraxinifolia* (Caucasian wingnut)	ISO 3133	TM	Pressing Temperature (110–170 °C)	16.63–26.74%	63.93–79.40%/157.06–252.15%
[35]	*Populus usbekistanica* (Poplar)	TS2474 TS2478	TM	Heat Treatment Temperature (120–200 °C)	144.55–188.18%	72.67–130.32%/− 2.58 to 71.64%
[88]	*Pinus Sylvestris* L. (Scots pine)	TS 2474 (1976)	TM	Pressing Temperature (120–160 °C)	83.72–88.37%	− 1.23 to 11.43%/− 6.08 to 42.56%

JIS Japanese Industrial Standards, *ISO* International Organization for Standardization, *TS* Turkish Standards Institution

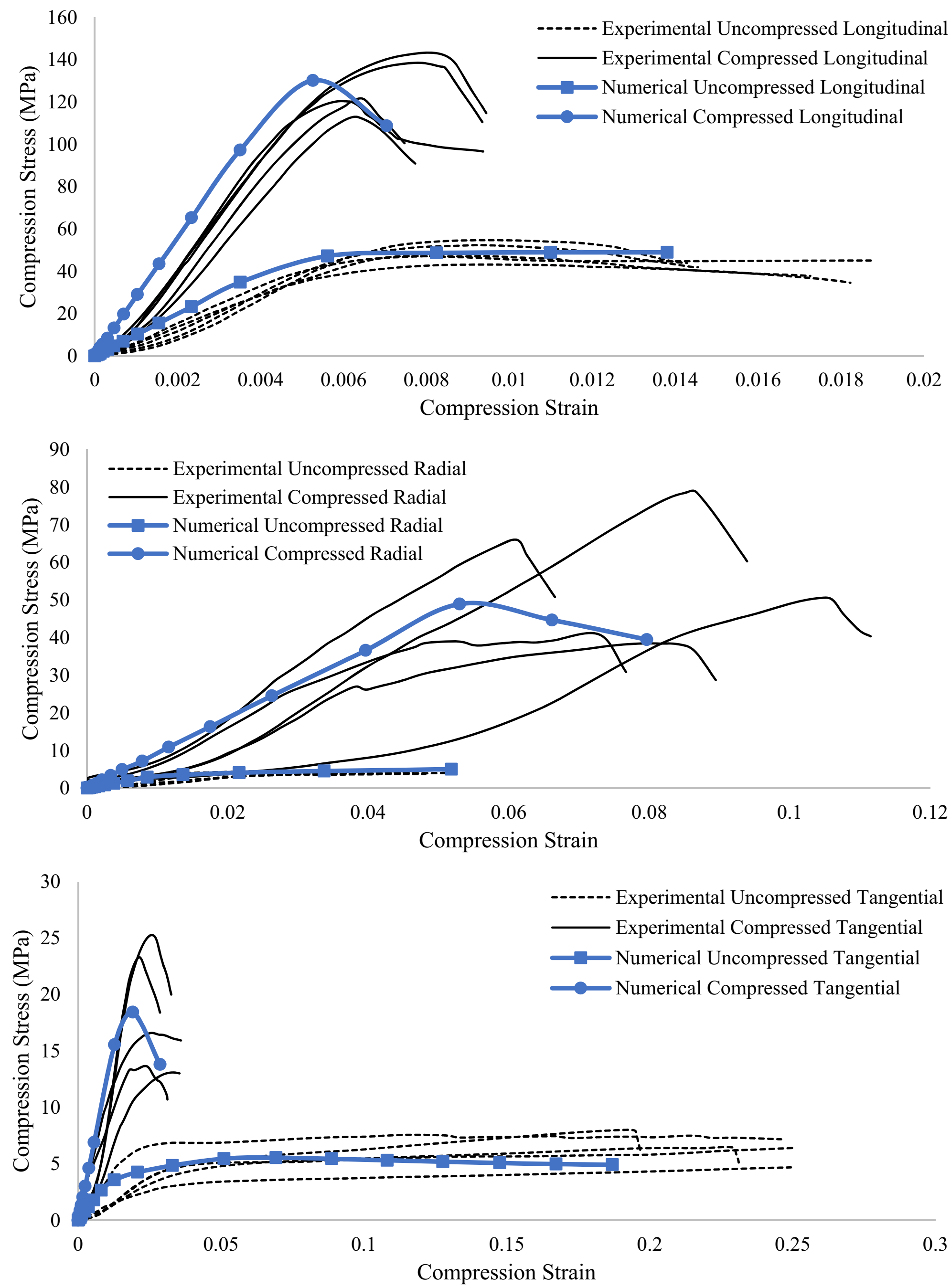


Fig. 9 Compression stress–strain diagrams (reproduced from Bouhala et al. [95])

direction shows a moderately ductile behaviour for 3 of the 5 samples, exhibiting elastic–plastic behaviour. Similar behaviour has been observed in the case of longitudinal compression. No specific failure modes were reported in the study.

Hardness and abrasion resistance

Hardness and abrasion resistance, similar to the strength properties of densified timber, improve with increasing density. The density profile of densified timber, peak density as well as the thickness of the densified zone are reported to influence the hardness of the timber [58, 96]. Tarkow and Seborg reported that abrasion resistance increased by at least 15 times as the density was doubled in densified timber; this abrasion resistance is higher than that of conventional hardwood maple [49]. The modified surface also featured increased hardness of up to 140% for surface-densified aspen [96]. It was observed that the elasticity of surface densified timber also increased with increasing hardness [55], forming a "rubber-like" layer that protects the surface of the material against impact [97]. Moreover, Laine et al. reported that changing both compression temperature and closing time can positively affect the hardness of the timber, as shown in Fig. 10 [55]. Higher temperatures and slower pressing speeds shifted the peak density away from the surface of the timber and lowered the hardness values. Lower temperatures and shorter closing times were reported to increase the peak density of the surface of the timber but increased the risk of breaking the cell wall structure.

CR is reported to have the least effect on the hardness property of surface densified timber. Rautkari et al. found that density of the surface layer was the most impactful property for the surface hardness of the timber, and CR had a limited effect to the hardness [98]. Results reported by Rautkari et al. shows almost no difference on hardness between different CRs (initial thicknesses from 18–22 mm to 15 mm) and different processes including thermal modification, densification, and the combination of both [98].

Dimensional stability

Background

The problem of dimensional stability had plagued early studies of timber densification. A phenomenon called 'shape memory' is present in densified timber [43], which is caused by internal stresses in the timber cells set through compression. The elastic energy stored in the crystalline regions of the microfibrils and lignin of timber is the main cause of SR in compressed timber. Moreover, the shape-fixation of densified timber is developed through the formation of hydrogen bonds between the deformed microfibrils and the lignin [39]. It was found that untreated and densified timber tend to recover from compression as soon as they are exposed to moisture and recover close to its original state when soaked in water [22]. Since then, several research carried out investigations to improve the dimensional stability of densified timber. Norimoto et al. suggested three mechanisms which are essential in permanently overcoming challenges in densified timber, such as the formation of cross-linkages between molecules of the timber matrix; the relaxation of the stresses stored in the timber matrix during compression; and the prevention of re-softening of the cell wall by increasing the hydrophobicity of the cell wall, as shown in Fig. 11 [24].

Development of densification techniques with improvements to dimensional stability

Early work on densified timber made use of phenol-formaldehyde resin impregnation to aid in the compression of timber through the plasticisation of cells. This densified timber product, called Compreg, not only has higher strength properties than untreated timber but also has increased dimensional stability as the phenolic-resin treatment tends to hold the timber in its compressed form largely eliminating SB of the compressed timber [22].

With the intention of decreasing the recovery of densified timber, Seborg et al. created Staypak, which is a

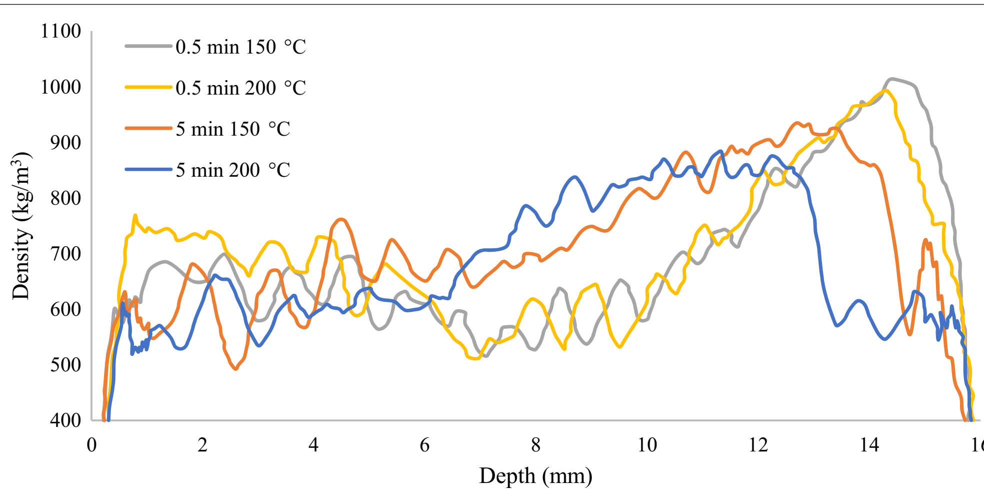


Fig. 10 Variations in density with depth in densified timber (reproduced from Laine et al. [55])

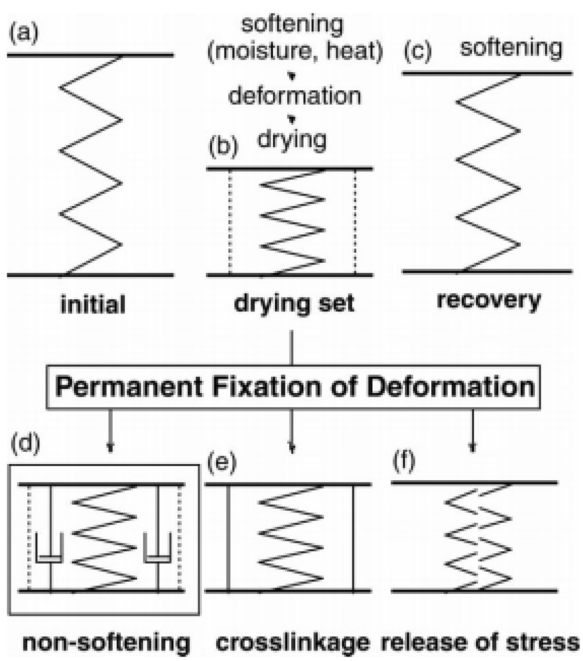


Fig. 11 Mechanisms of permanent fixation of deformation [37]

heat-stabilised compressed timber that is heated during the pressing process [20]. Although it does not tend to SB in the presence of moisture, Staypak has to be pressed with the optimum combination of MC, temperature and time of pressing to prevent SR. This effect is due to the release of stresses in the timber matrix resulting from compression.

Pre- and post-treatment of timber generally has a positive effect on the timber as well. Dwianto et al. found that pre-heating timber using three different methods (air heating, molten metal heating, and vacuum heating) resulted in almost complete and permanent fixation of the densified timber [81]. Similarly, Pelit et al. explored the use of the ThermoWood process applied after thermo-mechanical densification of *Scots pine* [82]. SB readings were at its lowest when heat treatment was applied at 210 °C. The study showed that approximately 18% of SR was seen in samples, heat treated at 210 °C. Similar results were observed in a study reported in 2016 on *Uludag fir* and *Black poplar* samples [83]. Another heating method is the use of oil as a medium. Oil-heat treatment (OHT) was applied as a post-heat treatment by Welzbacher et al. [86]. Results showed that both treatment temperatures and duration affected the SR of the specimens, with temperature having a larger impact on the stability of the timber. Densified untreated samples resulted in SRs greater than 15% compared to the 5% SR of the densified treated samples.

Sufficient plasticisation through steaming improved dimensional stability as well. Inoue et al. determined the effect of steaming on the dimensional stabilisation of *sugi*, with a CR of 50% at different temperatures for various lengths of time [36]. Longer steaming times and higher steam temperature led to substantially less recovery. After cyclic soaking tests, specimens steamed at 180 °C for 8 min recovered by approximately 10%, in comparison with unsteamed specimens recovering more than 80% of their initial thickness. Similar results were achieved in both pre-steaming and post-steaming compressed timber. Inoue et al. studied the effects and mechanisms of pre-steaming on the recovery of timber [37]. Specimens were pre-steamed in an autoclave at temperatures ranging from 120 to 220 °C for 10 min. Almost complete fixation was achieved by pre-steaming at 220 °C for 10 min.

Another process that targets the dimensional stability of densified timber is the THM process. Navi and Girardet investigated the mechanisms of permanent fixation using the THM process on small specimens of *beech, spruce*, and *pine* [43]. It was found that in THM treatments, dimensional stability benefits from increased heat, compressive stress and processing time. In comparison to thermal processes, THM's ability to retain moisture and confine the timber in saturated conditions plasticises the timber more and, in turn, enables densification at much lower pressures. This provided the timber with higher dimensional stability as the cell lumens of the timber completely closed due to the compression in combination with moisture in a closed environment. According to Navi and Heger, relaxation of the internal stresses was achieved through the weakening of the bonds of the hemicelluloses by hydrolysis and elution [39]. The THM process caused a reduction in the total pore volume and pore area [40]. It was inferred that a physio-chemical bonding occurred in the closed lumens which enables less SR for the timber to occur. In addition, with similar mechanics as THM, VTC densification also improved the dimensional stability of timber.

The use of chemicals, similar to Compreg, was explored in recent years. Inoue et al. explored the use of acetic anhydride at 120 °C with a CR of 50% to increase the dimensional stability of the acetylated densified timber [71]. The acetylation process prevents water molecules from entering the cell wall through substitution of the hydrophobic groups with hydroxyl groups. As shown in Fig. 12, acetylation is effective in preventing SR in a high moisture environment at a room temperature of 20 °C. However, this effect diminishes in the case of acetone soaking or boiling. Inoue et al. further studied the recovery behaviour of densified and acetylated timber using the non-softening mechanism [67]. A CR of 50% was used on the acetylated specimens, and different weight

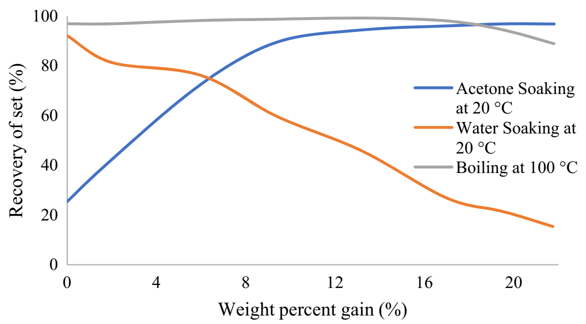


Fig. 12 Recovery of set from water soaking at 20 °C, boiling, and acetone soaking at 20 °C for acetylated timber (reproduced from Inoue et al. [71])

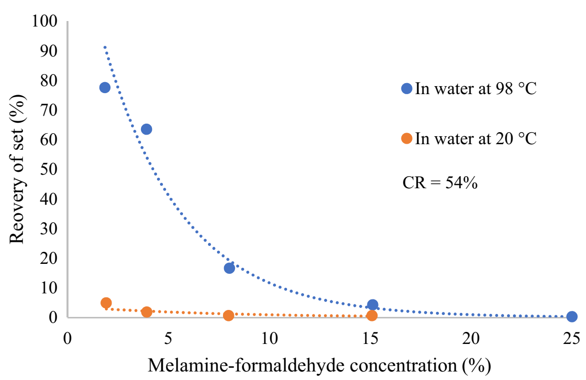


Fig. 13 Effect of MF concentration on SR (reproduced from Inoue et al. [75])

gain percentages of acetyl were used (up to 22%). Higher acetyl weight gain percentage resulted in a larger decrease in SR. In addition, recovery at room temperature further decreases as the acetyl weight gain percentage increases due to the improved hydrophobicity that acetic anhydride provides in the timber cell wall. Laine et al. also explored the use of acetylated timber in surface densification [99]. Average SR for untreated densified timber was approximately 75%, while the same for acetylated infused surface densified was significantly lower at 24%. One of the problems mentioned is the possibility of acetyl chemicals to be leached after water soaking, further increasing water uptake and, therefore, increasing SR after soaking cycles [99]. Furthermore, it was inferred that acetylated timber has a different viscoelastic response which leads to different reactions in the inner stresses of the timber. This is due to the transformation of the hydroxyl groups in the timber into acetyl groups, influencing the SR mechanism in acetylated timber. MF resin was also used to improve the dimensional stability of compressed timber. Inoue et al. investigated the use of MF resins as a fixation tool for densified specimens and found that pre-treatment using MF resins was effective in increasing the dimensional stability of densified timber [75]. MF treated timber achieved excellent SR percentages with an 8% solution when tested in 20 °C temperature water, and a 25% solution was required to permanently fixate the specimens in boiling water, as shown in Fig. 13.

Compreg-like products were further improved using lignin removal treatments, such as $NaClO_2$, facilitating the plasticisation of the cell wall and enabling compression at pressing pressures as low as 1 MPa [100]. The deformation behaviour of $NaClO_2$ treated PF resin-impregnated timber was further studied by Shams et al. [100]. The treatment reduced both the thickness swelling and water absorption of the timber compared to the untreated specimens. It was found that $NaClO_2$ treatment in conjunction with low molecular weight PF resin enabled densified timber to exhibit high dimensional stability due to the bulk product forming after curing of the resin. Various other chemicals were used to treat SR as well. Song et al. used a chemical treatment of sodium hydroxide and sodium sulphite to manufacture compressed timber [94]. Exposure to 95% RH for 128 h resulted in the treated and densified timber to recover approximately 0.9% of the CR. In addition, surface painting of the densified timber formed a protective barrier for the timber. After exposure to 95% RH for 128 h, no thickness swelling was seen in the painted specimens. Another research explored the use of water repellents, such as paraffin, linseed oil, and styrene. Pelit and Emiroglu investigated the effects of these water repellents on the hygroscopicity and dimensional stability of *fir* and *aspen* [101, 102]. The results showed that SR and SB generally reduced with the use of impregnation pre-treatments, and better results were seen with the use of linseed oil treatments as opposed to paraffin.

With the development of nanotechnology, nano particles are now used as resins to impregnate timber and improve physical and mechanical properties of timber. Rassam et al. investigated the effect of nano-silver impregnation on the properties of compressed low density timber species [103]. It was concluded that nano silver treated specimens that were compressed at 150 °C for 4 h achieved only 0.04% SB. One reason for the significant decrease in SB is the viscose deformation of timber becoming larger than the elastic deformation after a certain compression time. In this case, a press duration of 4 h resulted in greater reduction than a press duration of 1 h. It was inferred that silver ions block the chain movements of the timber by linking to the hydroxyl groups in timber and minimise the SB of the densified timber. Another research involved the densification of nano-aluminium-oxide impregnated timber [104]. It was found that instantaneous SB and SR decreased with the use of nano-aluminium-oxide impregnation combined with vapour pre-treatment, and longer vapour pre-treatment times resulted in an improvement on SB and SR percentages.

Summary on the properties of densified timber

The properties of densified timber are affected by different internal and external factors, such as the species of the timber, initial density, CR, pressing temperature, and use of pre-treatment chemicals. General improvements on densified timber include the increase in MOE, MOR, hardness and abrasion resistance, as well as bending and shear strengths. Manufacturing parameters, such as pressing temperature and CR tend to have a larger effect on MOE and MOR, requiring a minimum of 15% CR at 100 °C pressing temperature to achieve positive results. In addition, thermal pre-treatments are heavily reliant on the temperature due to the risk of thermal degradation and cell wall fracturing at higher temperatures. The use of VTC and THM densification resolves this risk, since no cell wall fractures are seen after densification due to the compression at or above the T_g. This indicates the importance of the manufacturing parameters in connection with the properties of densified timber. THM densification also produce improvements on density, shear strength, and MOE over the earlier forms of densification processes.

Usage of suitable chemicals at an appropriate proportion also tend to improve the strength properties in conjunction with densification. The chemicals act as a plasticiser that alters the interactive forces of timber constituents. Resin concentrations tend to lower the pressure required to collapse the cell wall of the timber. This enables the use of lower pressures with increasing resin concentrations [92]. Despite the use of lower pressures and temperatures, chemical treatment of the timber enables a higher CR due to the partial removal of lignin and cellulose, and thus creating a stronger densified timber [94].

Previous research on densified timber mainly addressed the issue of dimensional stability and the occurrence of SR. Dimensional stability is mainly affected by the type of process used to densify the timber and is predominantly fixed by decreasing the hygroscopicity of timber, formation of cross-linkages in the molecules, and the release of stress accumulated during compression. The development of the aforementioned processes revolves around these mechanisms to set the timber in its compressed state. Early work on densified timber required an optimum combination of MC, temperature, and pressing time to decrease the recovery of the timber from compression. Advancements on densification methods and the use of chemicals improved the SR and SB of densified timber due to the sufficient plasticisation of timber in THM, VTC, and chemical methods, and the facilitation of complete compression of the cell lumens of the timber. Pre-treatment and post-treatment of timber through different means also affected the dimensional stability of densified timber.

There is a lack of research in the serviceability aspect of densified timber; therefore, research on the acoustic properties, thermal properties, vibration performance, stress–strain behaviour, and durability of the densified timber is recommended. Furthermore, evaluation of different relationships between the material properties can be done to create a generalised model predicting the various properties of densified timber. A relationship between the virgin material and the densified material must be established to successfully create a material model that can accurately predict the material characteristics of densified timber. This can lead to a more accurate prediction of densified timber properties.

Applications of densified timber

Adhesive free engineered wood products

Engineered wood products (EWPs) are being adopted as an alternative to steel and concrete due to their increased mechanical properties and environmental benefits. However, most of the EWPs use chemicals, such as adhesives to bond the timber laminates to their specified orientation. Guan et al. proposed an alternative, called Adhesive Free Engineered Wood Products (AFEWPs) that involves the use of compressed timber [105]. AFEWP laminated timber beams were manufactured using compressed timber dowels to hold the laminates together. The moisture dependent swelling and SB of the compressed timber dowels were utilised to ensure a tight fit. El-Houjeyri et al. characterised the use of compressed timber dowels in adhesive free laminated timber (AFLT) beams and found that the mechanical performance (MOE and MOR) of the compressed timber in three-point bending tests was improved by a factor of 2 compared to uncompressed timber [106].

Higher energy dissipation was also seen in the compressed timber. Bending and shear strength were comparable to the control specimens, and the failure mode was ductile due to the progressive deformation of the compressed dowels. Further work on AFLTs was done by Sotayo et al. and comparable results were seen [107]. Ductile failure was observed due to the slip characteristics of the fasteners during deformation. However, flexural modulus and flexural strength were significantly lower than Glulam. The number and size of the compressed timber dowels affected the flexural modulus of the AFLT beam. In addition, adhesive free cross-laminated timber (AFCLTs) was manufactured by Sotayo et al. [107]. Using a staggered dowel arrangement, three layers of laminates were combined to form a CLT arrangement. Results show that the AFCLT panels were inferior to their counterparts in terms of flexural modulus and flexural strength. One advantage is the ductility of the connections, as a result of the deformation of the compressed dowel around the embedment. Feng and Chiang examined the mechanical strength of CLTs made with densified timber [108]. Bending strength and stiffness of the CLT improved with the use of densified timber, with an increase of MOE and MOR by 21.3% and 13.4%, respectively. Furthermore, failure of densified CLT panels were mainly due to adhesive failure that propagated that led to splitting of the specimen in half. Similar work on the use of densified timber was conducted by Salca et al., wherein a densified plywood was manufactured and tested [109]. Results showed that MOE, bending strength and shear strength increased as well as the bonding quality of the adhesives between panels.

Timber connections

Several researchers have attempted to utilise densified timber as conventional connections in structures. Jung et al. investigated the structural performance of compressed timber as a shear dowel [110]. Results indicated that the double shear strength of the timber connection increased, including its load-carrying capacity. However, the increase in strength is offset by the decrease in ductility, requiring the base member to be designed appropriately to suit the properties of the compressed dowel. Further research on dowels involved the use of compressed wooden plates in a beam–beam moment connection [111]. In comparison to their steel counterparts, the tests showed similar failure modes in the system, demonstrating brittle failure. Densified dowels have also been used as a swelling connection in timber joints [112]. The research utilised the SR capacity of the densified timber and tailored it to a double shear lap joint. Due to the higher swelling pressure of the densified dowel, a higher joint stiffness and ultimate load were obtained. However, failure was obtained through the breakage of the connecting elements. A novel connection involving compressed wooden nails was developed by Riggio et al. With the increase in compression resistance of the timber, success was found in the installation of wooden nails into boards. However, the strength properties of the wooden nails were still inferior to steel nails, and offer only a weight advantage, recyclability, and corrosion resistance when compared to steel nails [113]. Densified nails were seen to be only applicable to moderately loaded elements, such as ancillary timber components.

Future use of densified timber

Ecological building material

The growing need for sustainable and environmentally friendly options for building materials has led researchers to explore the use of timber, a renewable and versatile raw material capable of both structural and design-based applications. EWPs such as CLTs, Glulam, and LVL have been produced to enhance the properties of timber, such as its dimensional stability, durability, mechanical properties; and it enables the production of larger and more complex structural materials. While these EWPs were introduced as alternatives to concrete and steel, mainly as a more sustainable building material, these materials are typically made using adhesives or metal fasteners. Due to these modifications and the toxic and the irritating nature of the adhesives used in these materials, adverse effects on the sustainability and the environmental impact of the EWPs are noted. This causes both health and environmental concerns on the use of these EWPs. Densified timber has the potential to address these issues as this material possesses both improved mechanical properties and low environmental impact as the modification only occurs through the use of the timber itself. However, this potential is not yet realised as research has barely scratched the surface on the different aspects of densification. Research on densified timber must emphasise on the mechanical aspect of the EWP, particularly the bending, compression, and tension behaviour of the timber for practical purposes. Process optimisation, industrialisation, and standardisation go hand in hand and must be investigated to develop the appropriate product properties and reduce the environmental impact and energy usage of the densification processes. It should be noted that one of the main purpose of densification is to develop an alternative to high strength timber. This, however, must not be reached at the expense of environmental sustainability. Therefore, further studies must be done in the pursuit of eco-friendly alternatives to the densification methods, including process optimisation, product optimisation, and investigation of the mechanical behaviour of densified timber.

Potential for circular economy

One of the environmental concepts that can lead the world into a more sustainable future is the use of circular economy to maximise the utilisation of resources. Circular economy enables the productive use of natural resources, avoids waste and pollution, and improves the recovery of materials in a system. Due to the nature of the manufacturing of densified timber, the potential of the material for use in a circular economy is high. With the exception of chemically impregnated densified timber, other types of densified timber are greener products in terms of sustainable production, use, and end of life. Densified timber can be reused and repurposed into new products due to the unaltered nature of the material. The use of densified timber essentially enables a cradle-to-cradle sustainability model rather than a linear or cradle to grave approach.

Recyclability

An unexplored area is the use of recovered timber as potential specimens for densification. Provided that the structural strength and the composition of the timber has not degraded through use and time, there is a possibility that recovered timber can be used for manufacturing densified timber, giving the material a new lease of life and implementing it into the built environment. The difficulty with this concept is the traceability of the materials after being built into the structure. Estimating the strength and decay of the used timber materials at the end of their design, due to the applied load and environmental effects will be the main challenge for this. Another important aspect is the selection of the most appropriate densification method to reuse these materials. In addition, there is currently no standard practice on the reuse of building materials. Further research must be done on the viability of recovered timber as a raw material for densified timber.

Conclusions

In this paper, the development and background of timber densification, including the different methods, effects, applications, and the future of the material were comprehensively reviewed and critically discussed.

Key points of timber densification are:

- Densified timber is manufactured by mechanical or chemical means, essentially through the removal of voids in the cellular structure of the timber.
- The properties, such as dimensional stability and mechanical strength of densified timber are dependent upon the parameters used during the process. In addition, different effects are also seen for various densification processes.
- Improvements on both MOE and MOR of the densified timber up to 200–300% are possible in comparison to virgin timber.

While several aspects of densification are known, the influence of densification on the mechanical behaviour of timber, process optimisation, industrialisation, and standardisation of densified timber are still to be researched and developed. Outcomes for the properties of densified timber are still unpredictable with large variations seen in the results of different studies. Densification is still in its infancy and development of this process requires an analysis of the different mechanical responses of densified timber, and the analysis of the manufacturing process as a whole, including sawmilling.

Abbreviations

AFEWP: Adhesive Free Engineered Wood Products; AFLT: Adhesive Free Laminated Timber; CLT: Cross-laminated Timber; CR: Compression Ratio; EWP: Engineered Wood Products; Glulam: Glue-laminated Timber; LVFT: Linear Vibration Friction Technology; LVL: Laminated Veneer Lumber; MC: Moisture Content; MF: Melamine-formaldehyde; MOE: Modulus of Elasticity; MOR: Modulus of Rupture; PF: Phenol-formaldehyde; RH: Relative Humidity; SB: Spring-back; SR: Set-recovery; THM: Thermo-hydro-mechanical Densification; TM: Thermo-mechanical densification; UV: Ultraviolet; VTC: Viscoelastic thermal compression.

Acknowledgements

Not applicable.

Authors' contributions

JPC reviewed, analysed, and collated all of the data and information that is discussed in the article. All authors read and approved the final manuscript.

Funding

This paper is funded by Deakin University, School of Engineering, Waurn Ponds, Victoria, Australia.

Availability of data and materials

The data sets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

On behalf of all authors, the corresponding author states that there is no conflict of interests. The authors have no relevant financial or non-financial interests to disclose. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Received: 14 December 2021 Accepted: 23 March 2022
Published online: 30 March 2022

References

1. Sandberg D, Kutnar A, Mantanis G (2017) Wood modification technologies—a review. IForest 10:895–908. https://doi.org/10.3832/ifor2380-010
2. Sotayo A, Bradley D, Bather M, Sareh P, Oudjene M, El-Houjeyri I, Harte A, Mehra S, O'Ceallaigh C, Haller P, Namari S, Makradi A, Belouettar S, Bouhala L, Deneufbourg F, Guan Z (2020) Review of state of the art of dowel laminated timber members and densified wood materials as sustainable engineered wood products for construction and building applications. Develop Built Environ 1:100004. https://doi.org/10.1016/j.dibe.2019.100004
3. Kutnar A, Sernek M (2007) Densification of wood. Zbornik Gozdarstva Lesarstva 82:53–62
4. Institute A, of Timber Construction, Linville J.D. (eds) (2012) Timber construction manual, 6th edn. Wiley, New York
5. Elsener R (2014) Material characterization of timber utility poles using experimental approaches. Timber. 168:8
6. Holmberg S, Persson K, Petersson H (1999) Nonlinear mechanical behaviour and analysis of wood and fibre materials. Comput Struct 72:459–480. https://doi.org/10.1016/S0045-7949(98)00331-9

7. Bootle KR (1983) Wood in Australia: types, properties and uses. McGraw-Hill Education, New York
8. Crews KI (2016) 12 - Nonconventional timber construction. In: Harries KA, Sharma B (eds) Nonconventional and Vernacular Construction Materials. Woodhead Publishing, pp 335–363
9. Salmén L (2004) Micromechanical understanding of the cell-wall structure. CR Biol 327:873–880. https://doi.org/10.1016/j.crvi.2004.03.010
10. Laine K (2014) Improving the properties of wood by surface densification. Dissertation, Aalto University
11. Fengel D, Wegener G (1983) Wood : chemistry, ultrastructure, reactions
12. Ramage MH, Burridge H, Busse-Wicher M, Fereday G, Reynolds T, Shah D, Wu G, Yu L, Fleming P, Densley-Tingley D, Allwood J, Dupree P, Linden PF, Scherman O (2017) The wood from the trees: The use of timber in construction. Renew Sustain Energy Rev 68:333–359. https://doi.org/10.1016/j.rser.2016.09.107
13. Winandy J, Rowell R (1984) The chemistry of wood strength. handbook of wood chemistry and wood composites, second edition. https://doi.org/10.1021/ba-1984-0207.ch005
14. Shmulsky R, Jones PD (2019) Forest products and wood science: an introduction. Wiley, Newark
15. Salmén L (1982) Temperature and water induced softening behaviour of wood fiber based materials. Dissertation, The Royal Institute of Technology
16. Back E, Salmén L (1982) Glass transitions of wood components hold implications for molding and pulping processes. Tappi J 65:107110
17. Kelley SS, Rials TG, Glasser WG (1987) Relaxation behaviour of the amorphous components of wood. J Mater Sci 22:617–624. https://doi.org/10.1007/BF01160778
18. Lenth CA, Kamke FA (2001) Moisture dependent softening behavior of wood. Wood Fiber Sci 33:492–507
19. Kultikova EV (1999) Structure and properties relationships of densified wood. Dissertation, Virginia Tech
20. Seborg RM, Millett MA, Stamm AJ (1956) Heat-stabilized compressed wood (staypak). Forest Products Laboratory, Wisconsin
21. Seborg RM, Tarkow H, Stamm AJ (1953) Effect of heat upon the dimensional stabilization of wood. J For Products Res Soc 3(9):59–67
22. Stamm AJ, Alfred J, Seborg RM (1955) Forest products laboratory resin-treated, laminated, compressed wood (compreg). Forest Products Laboratory, Wisconsin
23. Navi P, Girardet F (2000) Effects of thermo-hydro-mechanical treatment on the structure and properties of wood. Holzforschung 54:287–293. https://doi.org/10.1515/HF.2000.048
24. Norimoto M, Ota C, Akitsu H, Yamada T (1993) Permanent fixation of bending deformation in wood by heat treatment. Wood Res 79:23–33
25. Tabarsa T, Chui YH (1997) Effects of hot-pressing on properties of white spruce. For Prod J 47:71–76
26. Dwianto W, Norirnoto M, Morooka T, Tanaka F, Inoue M, Liu Y (1998) Radial compression of sugi wood (Cryptomeria japonica D. Don). Holz als Roh- und Werkstoff 56:403–411. https://doi.org/10.1007/s001070050342
27. Zhou Y, Fushitani M, Sato K, Ozawa M (2000) Bending creep behavior of hot-pressed wood under cyclic moisture change conditions. J Wood Sci 46:423–430. https://doi.org/10.1007/BF00765799
28. Kubojima Y, Ohtani T, Yoshihara H (2004) Effect of shear deflection on vibrational properties of compressed wood. Wood Sci Technol 38:237–244. https://doi.org/10.1007/s00226-004-0237-5
29. Tanaka K, Demoto Y, Ouchi J, Inoue M (2010) Strength property of densified sugi adopted as material of connector. In: Proceedings of the World Conference on Timber Engineering (WCTE), Trentino, 2010
30. Anshari B, Guan ZW, Kitamori A, Jung K, Hassel I, Komatsu K (2011) Mechanical and moisture-dependent swelling properties of compressed japanese cedar. Constr Build Mater 25:1718–1725. https://doi.org/10.1016/j.conbuildmat.2010.11.095
31. Hill CAS, Ramsay J, Keating B et al (2012) The water vapour sorption properties of thermally modified and densified wood. J Mater Sci 47:3191–3197
32. Santos CMT, Menezzi CHD, de Souza MR (2012) Properties of thermo-mechanically treated wood from pinus caribaea var. hondurensis. BioResources 7:1850–1865
33. Kiaei M, Rad MB, Amani N (2018) Influence of densification temperature on some physical and mechanical properties of pterocarya fraxinifolia wood. Wood Industry / Drvna Industrija 69:283–287. https://doi.org/10.5552/drind.2018.1750
34. Pelit H, Yorulmaz R (2019) Influence of densification on mechanical properties of thermally pretreated spruce and poplar wood. BioResources 14:9739–9754. https://doi.org/10.15376/biores.14.4.9739-9754
35. Sözbir GD, Bektaş İ, Ak AK (2019) Influence of combined heat treatment and densification on mechanical properties of poplar wood. Maderas 21:481–492. https://doi.org/10.4067/S0718-221X2019005000405
36. Inoue M, Norimoto M, Tanahashi M, Rowell RM (1993) Steam or heat fixation of compressed wood. Wood Fiber Sci 25:224–235
37. Inoue M, Sekino N, Morooka T, Rowell RM, Norimoto M (2008) Fixation of compressive deformation in wood by pre-steaming. J Trop For Sci 20:273–281
38. Heger F, Groux M, Girardet F, Welzbacher C, Rapp AO, Navi P (2004) Mechanical and durability performance of thm-densified wood. In: Final Workshop Cost Action E22: Environmental Optimization of Wood Protection, Lisboa, 2004
39. Navi P, Heger F (2004) Combined densification and thermo-hydro-mechanical processing of wood. MRS Bull 29:332–336. https://doi.org/10.1557/mrs2004.100
40. Bao M, Huang X, Jiang M, Yu W, Yu Y (2017) Effect of thermo-hydro-mechanical densification on microstructure and properties of poplar wood (populus tomentosa). J Wood Sci 63:591–605. https://doi.org/10.1007/s10086-017-1661-0
41. Yoshihara H, Tsunematsu S (2007) Bending and shear properties of compressed sitka spruce. Wood Sci Technol 41:117–131. https://doi.org/10.1007/s00226-006-0091-8
42. Fang C-H, Mariotti N, Cloutier A, Koubaa A, Blanchet P (2012) Densification of wood veneers by compression combined with heat and steam. Eur J Wood Prod 70:155–163. https://doi.org/10.1007/s00107-011-0524-4
43. Chen S, Obataya E, Matsuo-Ueda M (2018) Shape fixation of compressed wood by steaming: a mechanism of shape fixation by rearrangement of crystalline cellulose. Wood Sci Technol 52:1229–1241. https://doi.org/10.1007/s00226-018-1026-x
44. Skyba O, Schwarze F, Niemz P (2009) Physical and mechanical properties of Thermo-hygromechanically (THM) - Densified wood. Wood Research 54:1–18
45. Balasso M, Kutnar A, Niemelä EP, Mikuljan M, Nolan G, Kotlarewski N, Hunt M, Jacobs A, O'Reilly-Wapstra J (2020) Wood properties characterisation of thermo-hydro mechanical treated plantation and native tasmanian timber species. Forests 11:1–15. https://doi.org/10.3390/f11111189
46. Cao R, Marttila J, Möttönen V, Heräjärvi H, Ritvanen P, Verkasalo E (2020) Mechanical properties and water resistance of Vietnamese acacia and rubberwood after thermo-hygro-mechanical modification. Eur J Wood Wood Products 78:841–848. https://doi.org/10.1007/s00107-020-01552-7
47. Kamke F, Sizemore H (2004) Viscoelastic thermal compression of wood. US Patent 7,404,422 B2, 5 Feb 2004
48. Rautkari L, Laine K, Laflin N, Hughes M (2011) Surface modification of scots pine: the effect of process parameters on the through thickness density profile. J Mater Sci 46:4780–4786. https://doi.org/10.1007/s10853-011-5388-9
49. Tarkow H, Seborg RM (1968) Surface densification of wood. For Prod J 18:104–107
50. Rautkari L, Kutnar A, Hughes M, Kamke F (2010) Wood surface densification using different methods. In: 11th World Conference on Timber Engineering, Riva del Garda, 20–24 June 2010
51. Rautkari L, Properzi M, Pichelin F, Hughes M (2010) Properties and set-recovery of surface densified Norway spruce and European beech. Wood Sci Technol 44:679–691. https://doi.org/10.1007/s00226-009-0291-0
52. Gong M, Lamason C, Li L (2010) Interactive effect of surface densification and post-heat-treatment on aspen wood. J Mater Process Technol 210:293–296. https://doi.org/10.1016/j.jmatprotec.2009.09.013
53. Kutnar A, Rautkari L, Laine K, Hughes M (2012) Thermodynamic characteristics of surface densified solid Scots pine wood. Eur J Wood Wood Products 70:727–734. https://doi.org/10.1007/s00107-012-0609-8

54. Laine K, Belt T, Rautkari L et al (2013) Measuring the thickness swelling and set-recovery of densified and thermally modified Scots pine solid wood. J Mater Sci 48:8530–8538. https://doi.org/10.1007/s10853-013-7671-4
55. Laine K, Rautkari L, Hughes M (2013) The effect of process parameters on the hardness of surface densified Scots pine solid wood. Eur J Wood Prod 71:13–16. https://doi.org/10.1007/s00107-012-0649-0
56. Laine K, Rautkari L, Hughes M, Kutnar A (2013) Reducing the set-recovery of surface densified solid Scots pine wood by hydrothermal post-treatment. Eur J Wood Prod 71:17–23. https://doi.org/10.1007/s00107-012-0647-2
57. Laskowska A (2017) The influence of process parameters on the density profile and hardness of surface-densified birch wood (betula pendula roth). BioResources 12:6011–6023
58. Zhou Q, Chen C, Tu D, Zhu Z, Li K (2019) Surface densification of poplar solid wood: effects of the process parameters on the density profile and hardness. BioResources 14(2):4814–4831
59. Wang J, Cooper PA (2005) Vertical density profiles in thermally compressed balsam fir wood. For Prod J 55:65–68
60. Wang JY, Cooper PA (2005) Effect of grain orientation and surface wetting on vertical density profiles of thermally compressed fir and spruce. Holz als Roh - und Werkstoff 63:397–402. https://doi.org/10.1007/s00107-005-0034-3
61. Rowell R (1983) Chemical Modification of Wood. For Prod Abstr. https://doi.org/10.3139/9783446442504.022
62. Rowell R, Tillman A-M, Simonson R (1986) A simplified procedure for the acetylation of hardwood and softwood flaxes for flakeboard production. J Wood Chem Technol 6:427–448. https://doi.org/10.1080/02773818608085236
63. Youngquist J, Krzysik A, Rowell R (1986) Dimensional stability of acetylated aspen flakeboard. Wood Fibre Sci 18(1):90–98
64. Rowell R, Youngquist J, Rowell J, Hyatt J (1991) Dimensional stability of aspen fiberboard made from acetylated fiber. Wood Fibre Sci 23(4):558–566
65. Larsson P, Simonson R (1994) A study of strength, hardness and deformation of acetylated Scandinavian softwoods. Holz als Roh-und Werkstoff 52:83–86. https://doi.org/10.1007/BF02615470
66. Ramsden MJ, Blake FSR, Fey NJ (1997) The effect of acetylation on the mechanical properties, hydrophobicity, and dimensional stability of Pinus sylvestris. Wood SciTechnol 31:97–104. https://doi.org/10.1007/BF00705925
67. Inoue M, Morooka T, Rowell RM, Norimoto M, Englund F (2008) Mechanism of partial fixation of compressed wood based on a matrix non-softening method. Wood Mat Sci Eng 3:126–130. https://doi.org/10.1080/17480270903020347
68. Rowell R (2014) Acetylation of wood–a review. Int J Lignocellulosic Products 1(1):1–27
69. Stamm AJ, Alfred J, Seborg RM (1942) Forest products laboratory resin-treated wood (impreg). Forest Products Laboratory, Wisconsin
70. Stamm AJ, Burr HK, Kline AA (1955) Heat stabilized wood (staybwood). Forest Products Laboratory, Wisconsin
71. Inoue M, Morooka T, Norimoto M, Rowell R, Egawa G (1992) Permanent fixation of compressive deformation of wood. FRI Bulletin 176:181–189
72. Shams MdI, Yano H (2011) Compressive deformation of phenol formaldehyde (PF) resin-impregnated wood related to the molecular weight of resin. Wood Sci Technol 45:73–81. https://doi.org/10.1007/s00226-010-0310-1
73. Yue K, Wu J, Xu L, Tang Z, Chen Z, Liu W, Wang L (2020) Use impregnation and densification to improve mechanical properties and combustion performance of Chinese fir. Constr Build Mater 241:118101. https://doi.org/10.1016/j.conbuildmat.2020.118101
74. Schwarzkopf M (2021) Densified wood impregnated with phenol resin for reduced set-recovery. Wood Mat Sci Eng 16:35–41. https://doi.org/10.1080/17480272.2020.1729236
75. Inoue M, Ogata S, Kawai S, Rowell R, Norimoto M (1993) fixation of compressed wood using melamine-formaldehyde resin. Wood Fiber Sci 25:404–410
76. Gindl W, Zargar-Yaghubi F, Wimmer R (2003) Impregnation of softwood cell walls with melamine-formaldehyde resin. Biores Technol 87:325–330. https://doi.org/10.1016/S0960-8524(02)00233-X
77. Lykidis C, Kotrotsiou K, Tsichlakis A (2020) Reducing set-recovery of compressively densified poplar wood by impregnation–modification with melamine–formaldehyde resin. Wood Mat Sci Eng 15:269–277. https://doi.org/10.1080/17480272.2019.1594365
78. Lykidis C, Moya R, Tenorio C (2020) The effect of melamine formaldehyde impregnation and hot-pressing parameters on the density profile of densified poplar wood. Eur J Wood Prod 78:433–440. https://doi.org/10.1007/s00107-020-01515-y
79. Esteves BM, Pereira HM (2008) Wood modification by heat treatment: A review. BioRes 4:370–404. https://doi.org/10.15376/biores.4.1.370-404
80. Laine K, Segerholm K, Walinder M, Rautkari L, Hughes M (2016) Wood densification and thermal modification: hardness, set-recovery and micromorphology. Wood Sci Technol. https://doi.org/10.1007/s00226-016-0835-z
81. Dwianto W, Inoue M, Tanaka F, Norimoto M (1997) Fixation of compressive deformation of wood by heat treatment. J Japan Wood Res Soc 43(4):303–309
82. Pelit H, Sönmez A, Budakçı M (2014) Effects of Thermowood® process combined with thermo-mechanical densification on some physical properties of scots pine (pinus sylvestris l.). BioResources 9:4552–4567
83. Pelit H, Budakci M, Sonmez A (2016) Effects of heat post-treatment on dimensional stability and water absorption behaviours of mechanically densified uludag fir and black poplar woods. BioResources 11:3215–3229
84. Kutnar A, Kamke FA, Sernek M (2008) The mechanical properties of densified VTC wood relevant for structural composites. Holz Roh Werkst 66:439–446. https://doi.org/10.1007/s00107-008-0259-z
85. Neyses B (2019) Surface densification of solid wood paving the way towards industrial implementation. Dissertation, Luleå University of Technology
86. Welzbacher CR, Wehsener J, Rapp AO, Haller P (2008) Thermo- mechanical densification combined with thermal modification of Norway spruce (Picea abies Karst) in industrial scale – dimensional stability and durability aspects. Holz als Roh - und Werkstoff 66:39–49. https://doi.org/10.1007/s00107-007-0198-0
87. Alen R, Kotilainen R, Zaman A (2002) Thermochemical behavior of Norway spruce (Picea abies) at 180–225 °C. 9. https://doi.org/10.1007/s00226-001-0133-1
88. Ulker O, Imirzi O, Burdurlu E (2012) The effect of densification temperature on some physical and mechanical properties of scots pine (pinus sylvestris l). BioResources 7:5581–5592. https://doi.org/10.15376/biores.7.4.5581-5592
89. Kutnar A, Kamke FA (2012) Compression of wood under saturated steam, superheated steam, and transient conditions at 150°C, 160°C, and 170°C. Wood Sci Technol 46:73–88. https://doi.org/10.1007/s00226-010-0380-0
90. Kutnar A, Kamke FA (2012) Influence of temperature and steam environment on set recovery of compressive deformation of wood. Wood Sci Technol 46:953–964. https://doi.org/10.1007/s00226-011-0456-5
91. Shams MI, Yano H, Endou K (2004) Compressive deformation of wood impregnated with low molecular weight phenol formaldehyde (PF) resin I: effects of pressing pressure and pressure holding. J Wood Sci 50:337–342. https://doi.org/10.1007/s10086-003-0570-6
92. Shams MI, Yano H (2004) Compressive deformation of wood impregnated with low molecular weight phenol formaldehyde (PF) resin II: effects of processing parameters. J Wood Sci 50:343–350. https://doi.org/10.1007/s10086-003-0571-5
93. Shams MdI, Kagemori N, Yano H (2006) Compressive deformation of wood impregnated with low molecular weight phenol formaldehyde (PF) resin IV: Species dependency. J Wood Sci 52:179–183. https://doi.org/10.1007/s10086-005-0746-3
94. Song J, Chen C, Zhu S et al (2018) Processing bulk natural wood into a high-performance structural material. Nature 554:224–228. https://doi.org/10.1038/nature25476
95. Bouhala L, Fiorelli D, Makradi A, Belouettar S, Sotayo A, Bradley DF, Guan Z (2020) Advanced numerical investigation on adhesive free timber structures. Compos Struct 246:112389. https://doi.org/10.1016/j.compstruct.2020.112389
96. Lamason C, Gong M (2007) Optimization of pressing parameters for mechanically surface-densified aspen. For Prod J 57:64–68

97. Rautkari L, Properzi M, Pichelin F, Hughes M (2008) An innovative thermo densification method for wooden surfaces. In: Proceedings of 10th World Conference on Timber Engineering
98. Rautkari L, Laine K, Kutnar A, Medved S, Hughes M (2013) Hardness and density profile of surface densified and thermally modified Scots pine in relation to degree of densification. J Mater Sci 48:2370–2375. https://doi.org/10.1007/s10853-012-7019-5
99. Laine K, Segerholm K, Wålinder M, Rautkari L, Hughes M, Lankveld C (2016) Surface densification of acetylated wood. Eur J Wood Prod 74:829–835. https://doi.org/10.1007/s00107-016-1077-3
100. Shams MdI, Yano H, Endou K (2005) Compressive deformation of wood impregnated with low molecular weight phenol formaldehyde (PF) resin III: effects of sodium chlorite treatment. J Wood Sci 51:234–238. https://doi.org/10.1007/s10086-004-0638-y
101. Pelit H, Emiroglu F (2020) Density, hardness and strength properties of densified fir and aspen woods pretreated with water repellents. Holzforschung. https://doi.org/10.1515/hf-2020-0075
102. Pelit H, Emiroglu F (2020) Effect of water repellents on hygroscopicity and dimensional stability of densified fir and aspen woods. Drvna Industrija 71:29–40. https://doi.org/10.5552/drvind.2020.1901
103. Rassam G, Ghofrani M, Taghiyari HR, Jamnani B, Khajeh MA (2012) Mechanical performance and dimensional stability of nano-silver impregnated densified spruce wood. Eur J Wood Prod 70:595–600. https://doi.org/10.1007/s00107-011-0590-7
104. Taghiyari HR, Rassam G, Ahmadi-DavazdahEmam K (2017) Effects of densification on untreated and nano-aluminum-oxide impregnated poplar wood. J For Res 28:403–410. https://doi.org/10.1007/s11676-016-0321-3
105. Guan Z, Sotayo A, Oudjene M, El-Houjeyri I, Harte AM, Mehra S, Namari S, Makradi A, Belouettar S, Deneufbourg F (2018) Development of adhesive free engineered wood products-towards adhesive free timber buildings. In 2018 World Conference on Timber Engineering, Seoul, 20–23 August 2018
106. El-Houjeyri I, Thi V-D, Oudjene M, Khelifa M, Rogaume Y, Sotayo A, Guan Z (2019) Experimental investigations on adhesive free laminated oak timber beams and timber-to-timber joints assembled using thermo-mechanically compressed wood dowels. Constr Build Mater 222:288–299. https://doi.org/10.1016/j.conbuildmat.2019.05.163
107. Sotayo A, Bradley DF, Bather M, Oudjene M, El-Houjeyri I, Guan Z (2020) Development and structural behaviour of adhesive free laminated timber beams and cross laminated panels. Constr Build Mater 259:119821. https://doi.org/10.1016/j.conbuildmat.2020.119821
108. Feng TY, Chiang LK (2020) Effects of densification on low-density plantation species for cross-laminated timber. AIP Conf Proc 2284:020001. https://doi.org/10.1063/5.0029041
109. Salca E-A, Bekhta P, Seblii Y (2020) The effect of veneer densification temperature and wood species on the plywood properties made from alternate layers of densified and non-densified veneers. Forests 11:700. https://doi.org/10.3390/f11060700
110. Jung K, Kitamori A, Komatsu K (2008) Evaluation on structural performance of compressed wood as shear dowel. Holzforschung 62:461–467. https://doi.org/10.1515/HF.2008.073
111. Mehra S, O'Ceallaigh C, Guan Z, Sotayo A (2018) An investigation of the structural behaviour of beam-beam connection systems utilising compressed wood dowels and plates. In 21st International Conference on Composite Structures, Bologna, 4–7 September 2018
112. Grönquist P, Schnider T, Thoma A, Gramazio F, Kohler M, Burgert I, Rüggeberg M (2019) Investigations on densified beech wood for application as a swelling dowel in timber joints. Holzforschung. https://doi.org/10.1515/hf-2018-0106
113. Riggio M, Sandak J, Sandak A (2016) Densified wooden nails for new timber assemblies and restoration works: A pilot research. Constr Build Mater 102:1084–1092. https://doi.org/10.1016/j.conbuildmat.2015.06.045

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.