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Densification of wood

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Abstract

The paper treats the processes involved in wood densification and provides a summary of the state-of-the-art, as presented in the literature, with regard to densification as achieved by compression, accompanied by some form of hydrothermal treatment. The viscoelastic nature of wood is discussed, together with its thermal softening and typical stress-strain relationships. The properties of densified wood products depend, apart from processing parameters, on various anatomical features such as density, the percentage of late wood material, ray volume and the loading direction. The problems associated with wood stabilization after densification are also treated. Relevant examples of wood densification from fundamental research, and the results of applied studies significant for everyday practice, are presented. A special focus is given on the process of viscoelastic thermal compression (VTC) of wood.

Key words: wood, densification, VTC, softening, transverse compression, viscoelasticity, glass transition temperature

Zgoščevanje lesa

Izvleček

Članek obravnava procese, ki potekajo med postopkom zgoščevanja lesa, in podaja pregled dosežkov relevantnih raziskav, v katerih je bilo proučevano zgoščevanje lesa s kombiniranim postopkom hidrotermične obdelave in stiskanja. Predstavljena je viskoelastična narava lesa, skupaj s toplotnim mehčanjem oziroma plastifikacijo. Prikazane so značilne zveze med napetostjo in deformacijo lesa pri zgoščevanju. Pojasnjen je vpliv tehnoloških parametrov zgoščevanja in inherentnih značilnosti lesa, kot so gostota, odstotek kasnega lesa, delež trakovnega tkiva in smer obremenjevanja na končne lastnosti zgoščenega proizvoda. Članek obravnava tudi problem stabilizacije lesa po postopku zgoščevanja. Predstavljeni so relevantni primeri zgoščevanja lesa temeljnih raziskav in rezultati študij, ki so pomembni za aplikacijo. Podan je podroben opis procesa viskoelastične toplotne zgostitve (VTC) lesa.

Ključne besede: *les, zgoščevanje, VTC, mehčanje, prečno stiskanje, viskoelastičnost, temperatura steklastega prehoda*

1 Introduction

1 Uvod

Most mechanical properties of wood are correlated to its density (e.g. the crushing strength of wood increases proportionally with its density). High density wood is required for structural applications and where wear resistance is important. Since increasing the density of wood enhances its mechanical properties and improves the hardness of wood, many attempts have been made to develop a suitable process for the densification of wood (BLOMBERG / PERSSON 2004). Densification makes it possible for low-density woods to be substituted for harder species so that low-density and commercially uninteresting wood species can be modified into high performance and high value products. Wood species with high density, too, can be further improved in strength and hardness through densification (BLOMBERG / PERSSON / BLOMBERG 2005). Densified wood products can be competitive for purposes where wood is generally considered to be too soft or too weak (e.g. for structural applications where a sufficient strength, stiffness, and durability are required).

The concept of wood densification has been known since 1900, when the first patented densification procedures appeared (KOLLMANN / KUENZI / STAMM 1975; pages 139–149). None of these procedures were put into continuous use because the phenomena involved were not completely understood (i.e. the patents were concerned almost entirely with the mechanics of compression, and did not adequately consider plasticization or stability of the products). Subsequent studies of the plasticization of wood and on the elimination of the springback effect resulted in improved products. During the period between 1930 and 1960, many attempts such as heat treatment and different types of chemical treatment, involving bulking of the cell wall using polar chemicals, were made to alter wood

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properties (MORSING 2000).

Interest in the densification of wood has increased in recent years due to increasing competition from other materials and the decrease in the quality of structural wood as a consequence of the harvesting of fast grown woods (MORSING 2000). The objective of this paper is to provide a survey on the literature that is concerned with the compression of wood for its densification; to present the principles of the wood densification by compression; and to present the viscoelastic thermal compression (VTC) process and the properties of VTC wood.

2 Wood densification

2 Zgoščevanje lesa

The densification of wood changes its properties, so that wood densification can be considered as a modification process. The broad range of possible wood modification treatments can be divided into three categories related to the mode of action of the chemicals (HOMAN / JORISSEN 2004):

1. Lumen filling with a substance.
2. Bulking to fill the cavities in the cell wall as well as the cell lumen.
3. Modifying treatments by which the chemical structures of the cell wall components (lignin, cellulose and hemicellulose) are altered and covalent bonds are formed. Modification within this category can be divided into heat treatments, chemical modification, and enzymatic treatments.

In general, wood densification is the process by which wood density is increased by compression of the wood, the impregnation of cell lumens with a fluid substance, or a combination of compression and impregnation (KOLLMANN / KUENZI / STAMM 1975, pages 139–149). Densification of wood can be achieved by impregnating its void volume with polymers, molten natural resins, waxes, sulphur, and even molten metals (KULTIKOVA 1999). Wood can also be densified by compressing it in a transverse direction under conditions that do not cause damage to the cell wall (KOLLMANN / KUENZI / STAMM 1975; page 139). The processing technique of densifying wood by compression requires four steps (MORSING 2000):

1. softening or plasticization of the cell wall,
2. compression perpendicular to the grain in the softened state,
3. setting by cooling and drying in the deformed state, and
4. fixation of the deformed state.

3 Wood in transverse compression

3 Obnašanje lesa pri prečni kompresiji

This section describes the properties of wood that are important for the production of densified wood by compression. High density, strength and dimensional stability of densified wood can only be attained if all the relevant characteristics of wood (structural, chemical, physical, mechanical, rheological, etc.) are considered.

3.1 Viscoelastic behaviour of wood

3.1 Koelastično obnašanje lesa

Wood is termed as a viscoelastic material because its mechanical behaviour is between the behaviour of linear elastic solids and viscous fluids (WOLCOTT / KAMKE / DILLARD 1994). Owing to the viscoelastic nature of wood, its mechanical properties depend on time, temperature and moisture. In relative terms, at short times, low temperatures and low moisture contents, wood exhibits glassy behaviour that can be characterized as stiff and brittle. At long times, high temperatures and high moisture contents, wood exhibits rubbery behaviour that can be characterized as compliant. The transition phase occurs between these two distinct regions; the temperature associated with the phase change being typically called the glass transition temperature T_g (WOLCOTT / KAMKE / DILLARD 1994). The glass transition temperature T_g, also known as the softening temperature, characterizes the softening behaviour of amorphous polymers. When the temperature of the polymer approaches T_g, the stiffness of the material decreases rapidly, corresponding to a marked increase in molecular motion (WOLCOTT 1989). Many properties of amorphous polymers, such as the elastic modulus, change dramatically when the material passes this softening point (Figure 1).

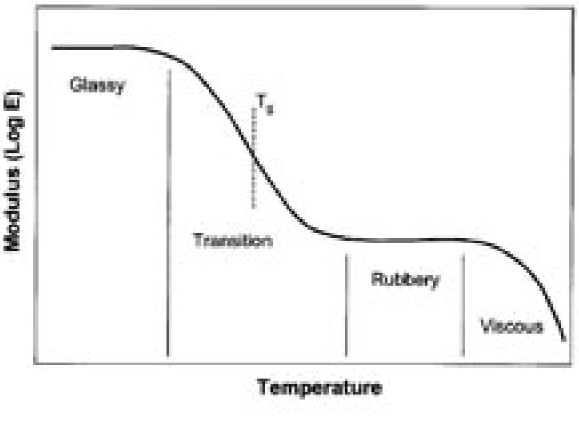

Figure 1: Variation of the relaxation modulus with temperature for an amorphous polymer (from LENTH 1999)

***Slika 1:** Spreminjanje relaksacijskega modula amorfnih polimerov s temperaturo (iz LENTH 1999)*

The viscoelastic nature of wood plays an important role in compression and densification. Brittle fractures in wood occur when the hemicelluloses and lignin are in the glassy phase, and the polymers are brittle. Temperatures higher than T_g promote polymer mobility and permit rearrangement of the molecules. When the wood temperature is above the glass transition temperature T_g of both amorphous polymers, large deformation can occur without fractures or with ductile fractures (WOLCOTT / KAMKE / DILLARD 1990).

HILLIS and ROSZA (1978) studied the influence of wood components on the softening of wood and suggested that moisture lowered the softening point of hemicelluloses and lignin in wood, which is above 160 °C when these two components are isolated from the wood. Hemicelluloses in the cell wall softened first (at 54–56 °C), which decreased the wood stiffness. This enabled wood fibres to adapt their cross-sectional shape to the applied forces. The softening of lignin (at 72–128 °C) in the cell wall and middle lamellae permitted further cross-sectional movement within and between the fibres. In the next study, HILLIS and ROZSA (1985) investigated the softening curves of wood in different growth rings taken from young radiate pine trees. They determined softening points of about 80 °C due to hemicelluloses and 100 °C due to lignin. Based on the results of HILLIS (1984), they attributed the differences in the softening curves to the differences in the chemistry of the hemicelluloses in sapwood and hardwood.

The softening temperature of wood is strongly influenced by its water content. Increasing moisture content decreases the glass transition temperature T_g of the amorphous components of wood, and vice versa (Figure 2). ÖSTBERG, SALMEN and TERLECKI (1990) showed that increasing moisture content decreases the softening temperature of spruce and birch. Water molecules plasticize wood polymers. Moisture forms secondary bonds with the polar groups in the polymer molecules, and spreads them apart, thus reducing the secondary bonding between the polymer chains and providing more room for the polymer molecules to move around. Moisture thus increases the free volume of the system. The wood becomes more easily deformed (MORSING 2000) and the transition temperature is lowered (SADOH 1981).

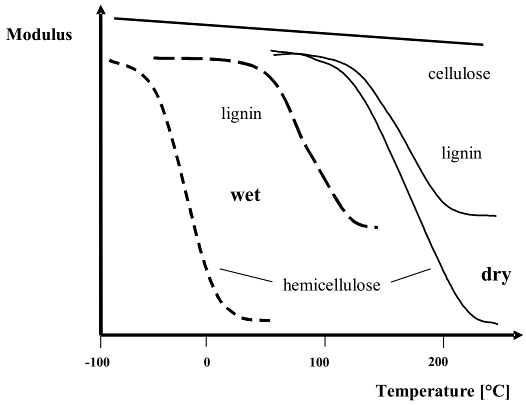

Figure 2: The glass-transition temperature of lignin as a function of moisture content (from MORSING 2000)

Slika 2: *Temperatura točke steklastega prehoda lignina kot funkcija vlažnosti (iz MORSING 2000)*

LENTH (1999) investigated the thermal softening behaviour of the juvenile and mature wood of southern pine and yellow-poplar at four moisture levels between 0 and 20% by means of dielectric thermal analysis (DETA). He established that the softening of amorphous wood components in the range of 20 to 200 °C coincides with the characteristic glass transition temperatures (T_g).

Because of its viscoelastic nature, wood also exhibits rheological properties such as creep and relaxation. The strain-time curve of wood under a compressive load can be divided into four parts: initial elastic deformation, viscoelastic deformation, final elastic springback and time-dependent springback or creep recovery (TANG / SIMPSON 1990). Viscoelastic behaviour results in densification due to the transverse compression of the constituent wood elements. Wood densification can have both permanent and recoverable components, which together have a significant influence on the physical and mechanical properties of the composite product (LENTH / KAMKE 2001a).

3.2 Stress-strain relationship of wood in compression

3.2 Zveza med napetostjo in deformacijo lesa pri kompresiji

During transverse compressive loading, a typical stress-strain curve of wood has three distinct regions (BODIG 1963, 1965, KENNEDY 1968, WOLCOTT / KAMKE / DILLARD 1994, UHMEIER / MOROOKA / NORIMOTO 1998, REITERER / STANZL-TSCHEGG 2001, NAIRN 2006), as shown in Figure 3. The initial part of the stress-strain curve for wood is a linear elastic region, in which the stress is directly proportional to strain. The second part is a "plastic" or collapse region, in which the stress is relatively constant even though strain increases rapidly (i.e. the wood continues to deform at a nearly constant stress). After the plastic region, the stress increases sharply with strain. This region is termed the densification region (TABARSA / CHUI 2000).

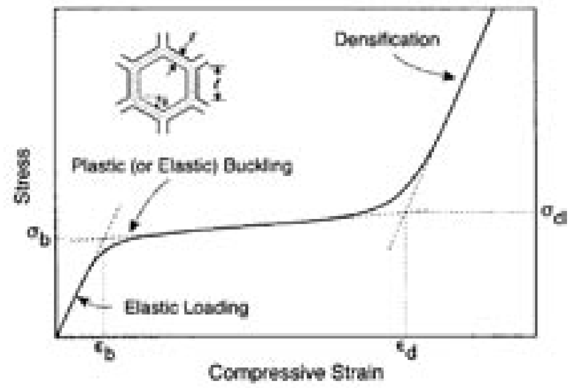

Figure 3: Schematic view of a transverse compression stress-strain curve for wood (from NAIRN 2006)

Slika 3: *Shematična predstavitev napetostno-deformacijske krivulje pri stiskanju lesa v prečni smeri (iz NAIRN 2006)*

A yield point is exhibited at the beginning of cellular collapse. When a majority of the cells have collapsed, densification begins (WOLCOTT / KAMKE / DILLARD 1994). During densification, the stress rapidly increases as a result of the elimination of air voids and compression of the solid wood structure – consolidation of the collapsed cell walls. Cellular collapse occurs by elastic buckling, plastic yielding, or brittle crushing, depending on the test conditions and the nature of the cell wall material (WOLCOTT *et al.* 1989).

The key details of the compression properties are dependent on various anatomical features of the wood specimen such as density, percentage of late wood material, ray volume and loading direction (NAIRN 2006). KUNESH (1968) noticed that in the radial compression of solid wood, first failure starts from the buckling of rays in an earlywood layer and results in progressive failure by buckling of the rays throughout the specimens. First failure in earlywood was also found by BODIG (1965). TABARSA and CHUI (2000) found that earlywood primarily controlled the elastic and plastic parts of the stress-strain response for white spruce under radial compression. The first collapse of the cellular structure, which signified the onset of the plastic region, occurred in the cell layer with the smallest gross density in the earlywood. The initial part of the densification region was largely an elastic response of the latewood to the compressive stress, and collapse of latewood cells may not have occurred due to their large wall thickness. In hardwoods, first failure was initiated in the largest vessels surrounded by thin-walled paratracheal parenchyma cells (TABARSA / CHUI 2001).

Several researchers have reported that wood responses differently to radial and tangential compression due to its anisotropic nature (KUNESH 1961, KENNEDY 1968, BODIG / JAYNE 1982, DINWOODIE 2000, TABARSA / CHUI 2001, WANG / COOPER 2005). In radial compression, the final consolidation stage is dominated by the elastic deformation of latewood, and in the tangential direction the final stage begins after readjustment of the latewood layer by buckling (TABARSA / CHUI 2001). REITERER and STANZL-TSCHEGG (2001) studied the compressive behaviour of spruce wood under uniaxial loading at different orientations with regard to the longitudinal and radial direction. Their results showed that the deformation patterns are highly different, depending on the orientation. In the case of loading in the longitudinal direction, buckling deformation and cracks occurred, but no densification could be found, whereas loading in the radial direction resulted in plastic yielding and (gradual) collapse of the wood cells starting in the earlywood region of a whole annual ring and followed by densification at higher strains. SCHREPFER and SCHWEINGRUBER (1998) studied the anatomical structures of reshaped press-dried wood. Earlywood cells were found to deform more easily than latewood cells, which resulted in zones of compressed cells next to zones of uncompressed cells, in wave-like patterns. A study by KULTIKOVA (1999) also showed wave-like patterns of compressed and uncompressed cell zones in densified wood. The different compressibility of wood tissue affects the distribution of void areas, and thus also the vertical density distributions and mechanical properties of compressed wood (LENTH / KAMKE 1996).

The type and amount of cell collapse have a very important effect on the physical and mechanical properties of densified wood (WOLCOTT 1989). Strength usually increases less than density in relative terms, since uniaxial compression of solid wood results in a general collapse of the structure and possibly also in crushing and checking (BLOMBERG / PERSSON / BLOMBERG 2005). This relation was found by PERKITNY and JABLONSKI (1984) for bending strength and axial (parallel to grain) compression strength. BLOMBERG, PERSON and BLOMBERG (2005) used the so-called strength potential index to quantify how much the strength of densified wood increased relative to what could be expected for non-densified wood of similar density.

Hydrothermal treatment has a strong influence on the mechanical behaviour of wood during compression/densification. Softening and degradation will occur depending on the conditions such as temperature, moisture, steam, and time (MORSING 2000). The degree of improvement in the properties of densified wood due to hydrothermal treatment is not only affected by softening but also by the amount of thermal degradation induced by the compression process (REYNOLDS 2004). Thermal degradation of amorphous wood components causes weight loss of wood, which can influence mechanical strength properties (JENNINGS 2003). For wet spruce in radial compression, a thermal degradation process was observed between 150 and 200 °C (UHMEIER /MOROOKA / NORIMOTO 1998).

3.3 Stabilization of densified wood

3.3 Stabilizacija zgoščenega lesa

One of the main problems associated with the process of compression is the springback effect, which occurs because the internal stresses introduced during compression are relieved when the wood is exposed to moisture (MORSING 2000). The compression-recovery behaviour of wood can be attributed to a combination of its cellular structure and the properties of the cell-wall polymers (WOLCOTT / SHUTLER 2003). Three basic mechanisms of fixing the compressive deformation can be identified (MORSING 2000):

1. preventing the wood from being re-softened by changing the hygroscopicity of the cell wall and thus making the cell wall inaccessible to water;
2. forming covalent crosslinks between the wood components in the deformed state;
3. releasing the elastic stresses and strains stored in the microfibrils and matrix during compression.

When compressed wood is exposed to moisture, reversible and irreversible swelling can occur. Reversible swelling is due to the hydroscopic nature of wood, whereas irreversible swelling is due to the springback of compressed (densified) wood. The most efficient way of reducing irreversible swelling is to minimize the build-up of internal stresses. Steam treatment prior to compression can markedly increase the compressibility of wood and in turn significantly reduce the build-up of internal stresses during hot pressing (HSU *et al.* 1988). INOUE *et al.* (1993) found that almost complete fixation can be achieved by post-steaming of compressed wood for 1 min at 200 °C or 8 min at 180 °C. MORSING (2000) assumed that the elimination of springback for steam-treated wood is the result of a break-down of the cross-links responsible for the memory effect in wood. This breakdown of primary bonds results in a slight flow of lignin and the formation of bonds in new positions. REYNOLDS (2004) investigated the swelling characteristics of the densified specimens and concluded that thickness swelling of less than 15% can only be achieved in the case of a temperature of 200 °C and 100% RH in the process of densification. DWIANTO *et al.* (1999) studied the mechanism of the permanent fixation of compressive deformation of wood by high temperature steaming for Sugi (*Cryptomeria japonica* D.Don). The results showed that the recovery of compressive deformation (strain recovery) decreased with steaming time and reached almost 0 in 10 min at 200 °C. The permanent fixation of deformation by steaming below 200 °C was considered to be due to the chain scission of hemicelluloses accompanied by a slight cleavage of lignin.

Just as steaming, heating, too, can induce permanent fixation of compressive deformation. The high temperature treatment of wood reduces its hygroscopicity, which is due to changes in the nature of the cellulose, hemicellulose, lignins and extractives (HILLIS 1984). SANTOS (2000) identified heat treatment as one of the most promising techniques, which could be used to increase dimensional stability of Eucalyptus wood, known for its characteristic low dimensional stability. Elimination of springback for the heat-treated wood is the result of the thermal degradation of the hygroscopic components in the cell wall, especially the hemicellulose (MORSING 2000).

4 Overview of wood densification processes in transverse compression

4 Pregled postopkov zgoščevanja lesa s stiskanjem v prečni smeri

The following section presents a literature survey on methods for densifying wood based on compression accompanied by some form of hydrothermal treatment. All forms of densification result in wood that has a lower volume of air space, which increases overall density.

The first patents for compressed wood in the United States were: Sears, *1900; Walch and Watts, 1923; Olesheimer, 1929; Brossman, 1931; Esselen, 1934; and Olson, 1934* (KOLLMANN / KUENZI / STAMM 1975, pp. 139–149). The first compressed solid wood in Europe was made in 1930 under the trade name "*Lignostone*" in Germany, and this type of technology still exists in Switzerland. The method is based on a simple process in which wood pieces are placed between the heated plates of a hydraulic jack, and compressed up to 250 kg/cm^2 in their radial direction. The temperature is raised to around 140 °C during a processing time of two hours. The wood used has been conditioned prior to treatment, with the moisture content being limited to 13%, thus eliminating the risk of explosion during pressing (NAVI / GIRARDET 2000). A similar laminated compressed wood product has been manufactured under the trade name "*Lignofol*". Similar materials, *Jicwood* and *Jablo*, have been in production in England for some years (KULTIKOVA 1999). Another method developed in the United States is "*Staypak*" (SEBORG / MILLET / STAMM 1945). The pressure applied in the production depends on the density, moisture content and temperature of the wood species used. At a temperature of 160 °C and a moisture content of 12%, SEBORG, MILLET and STAMM (1945) found that a specific gravity of 1.3 could be achieved at a pressure of 10–17 MPa on birch laminates, depending on the plasticizing conditions. But it has to be noted that temperature in the heat treatment applied in making "*Staypak*" is not sufficiently high for long enough periods of time to ensure dimensional stability. One of the problems associated with the production of "*Staypak*" is that the panels must be cooled to 100 °C or less while under full pressure. Due to the thermoplastic nature of the lignin, and because the moisture content of the wood is only slightly less after compression than prior to pressing, considerable springback will occur if the product is removed while still hot (KOLLMANN / KUENZI / STAMM 1975). These disadvantages of "*Staypak*" prevented this product from being generally adopted by industry.

The so far described densified products can be called thermo-mechanical (TM) densified wood (NAVI / GIRARDET 2000). Although this kind of treatment improves certain mechanical properties of wood, the deformation produced during the densification process is not stable, and recovers almost totally when the wood is re-moistened and heated. NAVI and GIRARDET (2000) developed a process for densifying wood by thermo-hydro-mechanical (THM) means. The product is called "*THM densified wood*". In the THM process, wood is densified under saturated vapour at a temperature of 150 °C. During the process, the specimen is confined under these conditions. The maximum compressive force applied during this process is about 130 kg/cm^2. Due to the characteristics of the hydro-thermal chamber used, heating of the specimen is performed directly by the pressurized vapour. The results of their tests showed that "*THM densified wood*" is less hydroscopic and more stable with small set-recovery. Their microscopic observations of cross-sections showed that TM densification caused vessel collapse, but that the cells were not deformed entirely, and the lumen stayed open. In the case of THM densification, the result was exactly the opposite. The authors also noted that although the same compressive force was applied to the earlywood and latewood, the lumen of the latewood cells were closed much more than those of the earlywood.

Recently, BLOMBERG and PERSSON (2004) patented a process for wood densification through semi-isostatic compression in a Quintus press. The name of the product is "*CaLignum*". By compressing wood in a Quintus press, density is increased and the strength properties are improved without inducing major checking. The pressure is applied by means of a flexible oil-filled rubber diaphragm, which makes harder structures less compressed than softer structures. This gives the compressed wood an irregular shape but homogenous density. The pressure rises successively up to 140 MPa, and is then immediately lowered to atmospheric pressure; the process takes about 3 min. No heating is needed. The moisture content of the wood is important and should be in the range between 4 and 18%. At the beginning of the compression process, the pressure is unidirectionally perpendicular to the press table. As the pressure increases due to the filling of the rubber diaphragm with oil, the diaphragm closes around all wood faces except the face placed on the rigid press table, and the pressure becomes isostatic.

In a further study, BLOMBERG (2005) showed that wood compressed at 140 MPa reached an almost compact structure and that springback was large when the pressure was released, indicating that the application of a higher pressure would not increase the plastic strain. To increase the plastic strain component and the final density, the process must be more destructive so that the wood structure collapses and the structure is less prone to spring back elastically. Isostatically compressed wood has also been studied by TRENARD (1977) and BUCUR, GARROS and BARLOW (2000), but their reports did not discuss the elastic springback that occurs at the release of pressure. They concluded that hydrostatic pressure has a large effect on the microstructure and mechanical properties of wood.

KAMKE and SIZEMORE (2005) developed a method for wood densification using a viscoelastic thermal compression (VTC) process. This process works by mechanically compressing wood to increase its density by between 100 and 300%. The key to the VTC device is the compressing of wood in a high pressure steam environment. This condition prevents the wood cells from fracturing under the extreme load. The compression is then permanently fixed using heat. The product is called "*viscoelastic thermal compressed wood*" ("*VTC wood*").

4.1 Process of Viscoelastic Thermal Compression of Wood

4.1 Proces viskoelastične toplotne zgostitve lesa

The VTC process increases the density of wood by raising the wood components by heat and humidity to (or above) their glass transition temperature, thereby softening the cell wall, and then compressing the wood components in a mechanical device – the hydraulic press. Pressure is applied by the operation of a remotely powered hydraulic cylinder. The rate of compression is controlled by adjusting the rate of flow of fluid into the hydraulic cylinder.

Densification of wood by VTC involves the following steps (KAMKE / SIZEMORE 2005*)*:

1. Heating and conditioning the wood to an elevated temperature and moisture content, such that the wood substance reaches or exceeds its glass transition temperature.
2. Inducing rapid vapour decompression and removal of the bound water in the cell wall. This step causes pronounced softening of the wood, which dramatically reduces the compression modulus of the wood perpendicular to the grain, and is referred to as mechanosorption. It occurs as a result of the rapid movement of water out of the wood cell wall. This movement of moisture creates a change in the distribution of the latter in the wood polymer structure, and retards the cell's ability to transfer stress and resist strain. In effect, the polymer molecules are able, to a great extent, to deform under the applied load without cleaving. Under such conditions the wood may be compressed, without cell wall fracture, to a greater extent than wood at the equivalent constant moisture content. Avoidance of cell wall fracture is important because greater increases in strength and stiffness are achieved when the cell wall remain intact.
3. Compressing the wood perpendicular to the grain while the wood is in a softened state. The glass transition temperature T_g is maintained during compression, so this step causes an increase in the density of the wood. A profile-imparting roller or plate can be used during compression.
4. Annealing the wood to allow relaxation of the remaining stresses. Annealing also promotes thermal degradation of the hemicelluloses in the wood component, thereby reducing the hygroscopicity of the wood. The remaining stresses in the wood are due to the stretched polymer molecules within the cell wall. With time and increased molecular motion, the polymer molecules slip into a more relaxed arrangement. Increasing the temperature increases molecular motion, and assists stress relaxation.
5. Cooling the wood to below its glass transition temperature, and increasing the moisture content, i.e. the wood is conditioned to the ambient temperature and humidity.

The local environment of moisture content and temperature influences densification, the density gradient formation and non-recoverable strain. The moisture content of wood in VTC process can be greater than the fibre saturation point (FSP), although about 15 to 30% is preferred. Specimens do not need to have uniform moisture content throughout their thickness, since the heating and conditioning zone will rapidly redistribute the moisture. As the phenomenon of mechanosorption is effective only during adsorption or desorption, the timing of desorption and subsequent compression is critical. Thin wood components are better suited for this process than thick ones, since thinner components will lose moisture more rapidly and uniformly. Consequently, the thickness of the wood components should typically be in the range between 3 mm and about 12 mm prior to compression. The desorption rate is roughly proportional to the thickness raised to the second power. The desorption rate is also increased in the case of a higher temperature of the wood at the time that it exits in the heating and conditioning zone. If the desorption is too rapid, the mechanosorption effect is not fully realized during the subsequent compression.

The desired temperature range in the heating and conditioning phase is therefore about 160 °C to 175 °C, and the pressure in a central section of the wood component may be within the range between 650 and about 2000 kPa. The wood compressing step can be performed so as to give a profile to the high density wood product. In the annealing zone the temperature is set within the range of between about 175 °C and about 225 °C, and the compressed wood is held under a mechanical pressure of between approximately 2000 and 4000 kPa. The level of load needed depends on the degree of compression that was achieved in the previous step. More compression requires a higher restraining force at this step. Stress relaxation depends on time, temperature and moisture content. Since the moisture content at this point is low, perhaps 2 percent, only temperature and time need to be controlled. Because of thermal degradation, many hydroxyl sites are lost at this step, and consequently, the ability of the wood to absorb moisture is reduced, resulting in improved dimensional stability of the compressed wood components upon exposure to moisture during use. At the end of this zone, the wood components are compressed to the desired degree of strain, the moisture content is almost zero, and the stress and hydroscopicity are low.

During the next step, the temperature is reduced to below the wood's glass transition temperature, and the moisture content is increased. Entering this zone the wood component is sprayed with water, which serves two purposes. Firstly, rapid evaporation consumes thermal energy, and reduces the temperature of the wood. Secondly, some of the water is absorbed, although not much due to the annealing process. The goal is to achieve a moisture content that will be in equilibrium with the surrounding environment at the completion of the process.

The degree of densification depends upon the basic wood density (CURRIER 1963, KAMKE / SIZEMORE 2005, LENTH / KAMKE 2001a and 2001b) and also on the species and type (adult, juvenile) of wood (KULTIKOVA 1999). Hence the amount by which density can be increased depends also on the type of the wood, on the thickness of the product, on the form of the wood in the product (i.e. on the size and shape of the wood elements), on previous treatments of the wood product, such as pressure and/or heat treatment, infusion with resin, and on the desired final density. In general, the increase in density is in the range of about 25% to about 500%, though preferably in the range of about 100% to about 200%.

4.1.1 Properties of VTC wood

4.1.1 Osti VTC lesa

The properties of VTC wood have not been fully researched, but the results of available research have shown that the anatomical and physical properties of wood are changed, and its mechanical properties are improved by viscoelastic thermal compression. The results of preliminary investigations into VTC properties have indicated that the tensile strength and stiffness of densified southern pine and yellow-poplar are considerably higher than those of undensified material (LENTH / KAMKE 2001a).

The compression and stabilization treatments used in the process of VTC have an effect on the morphology of wood (REYNOLDS 2004). The cellular structure of wood undergoes significant changes during compression at high temperature and under steam pressure. The high strain deforms the cell lumen and drastically reduces the total lumen volume. The type and amount of the cell collapse have a very important effect on the mechanical and physical properties of densified material (WOLCOTT 1989). KULTIKOVA (1999) investigated the effect of densification (using three different combinations of temperature and moisture) on the cellular structure and chemical composition of wood. The research made use of specimens of mature and juvenile southern pine (*Pinus taeda*) and yellow-poplar (*Liriodendron tulipifera*). It was established that densification treatments have a strong effect on the degree of damage to the cell walls. Wood compressed at 140 °C and 62% relative humidity showed elastic/plastic yielding of the cells. Wood compressed at 200 °C and 6.5% relative humidity showed brittle fracture of the cells. Wood compressed at 90 °C and 95% relative humidity showed cell separation and brittle fracture. An interesting finding was that temperature alone did not affect the wood structure. Chemical analysis showed no significant changes in the chemical composition of wood specimens subjected to 160 °C and pure steam for up to 8 hours. However, it was shown that wood that has undergone heat and steam treatment also undergoes changes in the crystallinity index (TANAHASHI *et al.* 1989). Such increases in crystallinity are likely to occur due to the mobility of the amorphous polymers above the glass transition temperature T_g, which allows for reorientation and crystallization of the polymers.

Due to the above-described modifications in structure and density, VTC wood exhibits different properties. The densification process results in wood with improved mechanical properties. KULTIKOVA (1999) reported that ultimate tensile stress and tensile modulus increased with densification, and that the strain level employed during compression has the greatest influence on increasing specific gravity and tensile properties.

KAMKE and SIZEMORE (2005) investigated the bending properties of a 3-layered laminated composite, with VTC wood in the two outer layers, and a strip of untreated yellow-poplar in the core layer. The modulus of elasticity and the modulus of rupture of the VTC composite increased by 130% and 91% respectively, compared to those of a matched composite sample that was made from untreated veneer.

The modified properties of VTC wood also affect its gluing properties. JENNINGS (1993) investigated the lap shear tension strengths of densified yellow-poplar as affected by resin type. Densified veneers bonded with either urea formaldehyde (UF) adhesive or phenol formaldehyde (PF) adhesive showed the same strength as non-densified veneers. Densified veneers bonded with polyvinyl acetate (PVAc) adhesive had higher strength than the control samples. JENNINGS (2003) also investigated surface energy and the bond performance of VTC wood. Surface energies of control, hydro-thermal treated and densified samples were compared. The results showed that hydro-thermal treatment significantly reduced the surface energy of yellow-poplar, whereas densified wood exhibited a very slight decrease in surface energy when compared to hydro-thermally treated wood. This led to the conclusion that the major cause of the surface energy reduction of densified wood was due to the hydro-thermal conditioning during the densification process. JENNINGS (2003) investigated the bond performance of VTC wood, and found that bond performance of VTC wood was similar (and in some cases even better) than that of the control yellow-poplar.

4.1.2 Use of VTC wood

4.1.2 Uporaba VTC lesa

VTC wood can be further processed in numerous ways for further use, including but not limited to: cutting and shaping the sheets or panels into various desired lengths or shapes; attaching multiple layers of the sheets together with similar or different materials to form a multi-layered laminate material of the desired thickness, “cosmetic” processing such as colouring, staining, etching, and overlaying. The high-density, dimensionally stable laminae produced by VTC process are of a quality that is suitable for use in laminated composites for structural inside and outside applications, as flooring and underlying materials, siding and roofing material, materials for constructing walls, etc. (KAMKE / SIZEMORE 2005).

5 Conclusions

5 Sklepi

The densification of wood enhances most of the latter's properties. Wood density can be increased by compression, by impregnation of the cell lumens with fluid substance, or by a combination of compression and impregnation. Densification by the transverse compression of wood consists of four stages: softening, compression, setting, and fixation of the compressed state. The viscoelastic nature of wood plays an important role in compression and densification. When the wood temperature is above the glass transition temperature of its amorphous polymers, then large deformation can occur without fractures. Compression properties depend mostly on various anatomical features of the wood specimen such as density, the percentage of late wood material, ray volume and loading direction. The springback effect, which is one of the main problems associated with the densification process, can be eliminated by steaming or heating, which can induce permanent fixation of the compressive deformation. Densification process, in which plasticizing of the wood and stabilization of the final product is adequately taken into account, is VTC densification process. Therefore VTC wood is definitely a product that could be easily adopted by the wood products industry, and could have a significant effect on it. The VTC densification process results in wood with a high density, improved mechanical properties, especially strength and high dimensional stability.

6 Povzetek

Mehanske lastnosti lesa so v neposredni zvezi z njegovo gostoto. Ker se z naraščajočo gostoto lesa izboljšujejo njegove mehanske lastnosti in trdota, so v preteklosti številni raziskovalci poskušali razviti primeren postopek zgoščevanja lesa. Zgoščevanje namreč omogoča modificiranje nizko gostotnih in komercialno nezanimivih lesnih vrst v visoko kakovostne produkte. Zgostitev lesa lahko dosežemo z impregnacijo, s stiskanjem v prečni smeri ali s kombinacijo impregniranja in stiskanja. Prvi postopki zgoščevanja lesa so bili razviti že v začetku 20. stoletja, vendar niso primerno upoštevali plastičnosti lesa in stabilizacije končnega produkta, zato v praksi niso bili nikoli uporabljeni. Zgoščevanje lesa s stiskanjem v prečni smeri, na kar smo se omejili v tem članku, je sestavljeno iz naslednjih korakov: mehčanje ali plastificiranje celičnih sten; stiskanje pravokotno na vlakna v zmehčanem stanju; sušenje in ohlajanje v deformiranem stanju ter fiksiranje deformiranega stanja. Visoka gostota, trdnost in dimenzijska stabilnost zgoščenega lesa je dosežena le z upoštevanjem strukturnih, kemijskih, fizikalnih, mehanskih in reoloških lastnosti lesa.

Zaradi viskoelastične narave lesa so njegove mehanske lastnosti odvisne od časa, temperature in vlažnosti. Pri relativno kratkotrajnih obremenitvah, nizki temperaturi in vlažnosti izkazuje les elastično obnašanje, ki ga lahko označimo kot togo in krhko. Pri dolgotrajnih obremenitvah, visokih temperaturah in vlažnostih pa izkazuje plastično oziroma viskozno obnašanje. V tem območju je les sposoben prenašati velike plastične deformacije. Med obema območjema je tako imenovana prehodna faza, za katero je značilna točka steklastega prehoda T_g (v resnici gre za območje), pri kateri se material zmehča. Posledično se ob prehodu T_g lesu spremenijo številne lastnosti.

Pri prečnem stiskanju lesa sta napetost in deformacija v značilnem odnosu. Napetostno deformacijska krivulja je sestavljena iz treh različnih območij. Začetni del napetostno deformacijske krivulje je linearno elastično območje, v katerem je napetost neposredno proporcionalna deformaciji. Sledi območje, v katerem je napetost relativno konstantna, čeprav deformacija hitro narašča. V tretjem območju napetost izrazito narašča z deformacijo. Pri tem je razmejitev območij napetostno deformacijske zveze odvisna od fizikalnih in anatomskih lastnosti lesa.

Glavni problem, povezan s postopkom stiskanja lesa, je t.i. »*springback efekt*« - ob izpostavitvi lesa vlažnosti se med postopkom stiskanja nastale notranje napetosti sprostijo. Ob izpostavitvi zgoščenega lesa vlažnosti se posledično pojavi debelinsko nabrekanje, kar je odvisno od celične strukture in lastnosti polimerov celičnih sten. Pri tem je treba razlikovati med nabrekanjem, ki je posledica higroskopske narave lesa, in ireverzibilnim nabrekanjem, ki je posledica springback-a stisnjenega oziroma zgoščenega lesa. Ireverzibilno nabrekanje lahko eliminiramo s parjenjem in segrevanjem ter tako dosežemo trajno fiksacijo tlačne deformacije.

Prvi patentirani postopki zgoščevanja lesa so bili opravljeni leta 1900 v Ameriki. Prvi postopek zgoščevanja s stiskanjem lesa v prečni smeri je bil »*Staypak*«. V Evropi je bil takšen postopek napravljen leta 1930 pod imenom »*Lignostone*«. Sledili so mu »*Lignofol*«, »*Jicwood*« in »*Jablo*«. Našteti postopki izboljšajo določene mehanske lastnosti lesa, vendar dosežena deformacija s postopkom zgoščevanja ni stabilna. Nedavno je bil razvit postopek »*THM*«, katerega produkt je stabilnejši in manj higroskopen zgoščen les. Visoko gostoto, trdnost in dimenzijsko stabilnost zgoščenega lesa pa je raziskovalcem uspelo doseči s postopkom »*viskoelastične toplotne zgostitve (VTC)*«. S kombinacijo pare, toplote in mehanskim stiskanjem se poveča gostota lesa za 100 do 300 %. Visoka temperatura in visok tlak vodne pare med postopkom stiskanja plastificirata les in preprečita lom lesnih celic pod ekstremnimi napetostmi. VTC-les ima spremenjene anatomske, fizikalne in mehanske lastnosti. Spremenjena anatomska zgradba se izraža v stisnjenih lumnih in deformiranih celičnih stenah, brez lomov. Dosedanje raziskave so dokazale, da ima VTC-les višjo natezno in upogibno trdnost kot nezgoščen les. Prav tako imajo višjo trdnost lesni kompoziti iz VTC-lesa. Spremenjene so tudi lastnosti površine VTC-lesa, kar vpliva na adhezijo pri lepljenju.

Zaradi visoke gostote, visokih mehanskih lastnosti in dobre dimenzijske stabilnosti ima VTC-les velik pomen v prihodnjem razvoju lesne industrije. Postopek VTC namreč omogoča modifikacijo komercialno nezanimivih lesnih vrst z nizko gostoto in njihovo uporabo v najrazličnejših tehnoloških namenih.

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