PROPERTIES OF WOOD AND WOOD BASED MATERIALS SUBJECTED TO THERMAL TREATMENTS UNDER VARIOUS CONDITIONS

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ABSTRACT: Thermal modification is a well-known process to change the dimensional stability, hygroscopicity, and biological resistance of wood due to chemical modifications of wood cell components. In this study, we reviewed several characteristics of heat-modified solid wood and wood-based panels under various temperatures, durations and pressure. Thermal compressing treatment could affect drying speed, equilibrium moisture content, dimensional stability, durability, surface quality, modulus of rupture, modulus of elasticity, janka hardness, surface abrasion strength, nail/screw withdrawal strength, and shear modulus of wood. The hygroscopicity of wood can be also affected by heat.

Key words: heat treatment, wood and wood based materials.

1. DEFINITION OF HEAT TREATMENTS

Wood has numerous applications due to a number of properties; however, it has some less desired properties such as low resistance against biodeterioration and weathering, dimensional stability, etc. There are various applications to overcome these negative characteristics of wood as well as to improve its other properties.

These applications can be categorized into two groups: Physical methods and chemical methods. In chemical methods, chemicals that react with wood cell components and modify wood structure are used. Depending on the structure of the chemicals used, several environmental problems may arise from these chemicals and they might be costly due to high prices of the chemicals. As a physical method, thermal modification also modifies wood structure; however, it can be completed without any chemical use and it is an environmentally-safe method for modification (Yıldız, 2002).

Even though thermal modification is long-known method, considerable amount of research has recently focused on this method and heat-modified wood has an important market share (Kantay ve Kartal, 2007).

Thermal modification can be performed in special thermal treatment kilns as well as under pressure and heat using special press. Considering special thermal treatment kilns, five processes have been developed and are currently available at industrial scale including Plato-Process (The Netherlands), Retification Process (France), Bois Perdure (France), OHT-Process (Germany), and ThermoWood Process (Finland) (Militz, 2002). The common ground of the five processes lies in modifying the chemical structure of lumber at temperatures ranging from 160 °C to 260 °C. The processes vary due to furnace design, type and condition of the heating gas, and treatment schedules.

2. THERMAL TREATMENTS AND THEIR EFFECTS ON WOOD

Heat treatment is one of the processes used to modify the properties of wood. Heat-treated wood is considered an eco-friendly alternative to chemically impregnated wood materials. The chemical modifications that occur in wood at high temperatures are accompanied by several favorable changes in its physical properties, including reduced shrinkage and swelling, improved biological durability, low equilibrium moisture content, enhanced weather resistance, a decorative dark color, improved thermal insulation properties, low pH, several extractives flowed from the wood, and better decay resistance (Rapp, 2001).

The extent of change in wood properties during heat treatment depends on the method of thermal modification, the wood species and its characteristic properties, the initial moisture content of the wood, the surrounding atmosphere, and treatment time and temperature. Treatment temperature has the strongest effect on many wood properties (Mitchell, 1988).

During heat-treatment a large number of chemical changes occur, including the degradation of the hemicelluloses components of wood (Viitaniemi, 1997b; Alen et al., 2002; Sivonen et al., 2002). Significant decrease of hemicelluloses content is also reported in the literature (Pavlo and Niemz, 2003). The hemicelluloses degrade first (between 160 and 260C) since their low molecular weight and their branching structure facilitates a faster degradation compared to the other components present in wood (Fengel and Wegener, 1984). As a consequence of chemical changes in wood's structure the physical properties of wood are also modified. The higher the heat-treating temperature and the longer the time, the more significant are the changes (Metsa-Kortelainen et al., 2006). Due to heat-treatment and thermal degradation, wood loses its weight. Also, heat treatment reduces the equilibrium moisture content of wood (Jamsa and Viitaniemi, 2001; Nakano and Miyazaki, 2003; Gosselink et al., 2004; Wang and Cooper, 2005; Metsa-Kortelainen et al., 2006) and improves its dimensional stability (Kollmann and Schneider, 1963; Viitaniemi et al., 1997; Epmeier et al., 2001; Yildiz, 2002; Bekhta and Niemz, 2003; Gonzalez-Pena et al., 2004; Wang and Cooper, 2005) and rot resistance (Kim et al., 1998; Kamdem et al., 2002; Hakkou et al., 2006), darkens wood's color, (Bekhta ve Niemz, 2003) and improve heat isolation.

One important disadvantage of thermal treatment is that it is resulted in decreased mechanical properties and more brittle structure (Kim et al., 1998; Kubojima et al., 2000; Bengtsson et. al., 2002; Unsal and Ayrilmis, 2005; Viitaniemi, 1997b; Bekhta and Niemz, 2003; Sailer et al., 2000; Shi et al., 2007). Although wettability decreases (Petrissans et. al., 2003; Sernek et al., 2004; Follrich et al., 2006; Gerardin et al., 2007; Hakkou et al., 2005a, b), the gluing process can be adapted for treated wood (Militz, 2002).

A wood surface, which is exposed to high temperature condition, can experience surface inactivation (Petrissans et al., 2003; Hakkou et al., 2005a). Inactivation of wood surfaces, which results in poor bond quality, is a time-dependent process accelerated by increasing temperature (Aydin, 2004). An inactivated wood surface can cause adhesion problems because of the interference with wetting, flow, and penetration of adhesive, and also interfere with the cure and resulting cohesive strength of the adhesive.

Using compression and temperature of wood purposes to increase its physical and mechanical properties. Thermally compressed wood is known as staypak (Seborg et al., 1945; Stamm, 1964), while compressed wood with phenol formaldehyde (PF) resin pretreatment is called compreg (Stamm and Harris, 1953; Stamm, 1964). Furrher studies were done by Tarkow and Seborg (1968) studying surface densification of wood. After 1980s compressed wood products for low density, and cheaper wood species were produced, especially for utilization some fast growing in Asia (Norimoto 1993; Wang et al. 2000; Norimoto 1994).

Due to improved properties of wood, thermally-modified wood is used for exterior cladding, doors and windows, garden furniture and decking material, sauna, flooring material, kitchen furniture, etc. (Viitaniemi, 2000). Production capacity of thermally-modified wood is 165.000 m^3 in 2001 and 265.000 m^3 in 2002 (Syrjanen ve Oy, 2001; Rapp, 2001).

Specifically for wood-based panels, there are several methods of treatment or strategies to improve dimensional stability which can be divided into three different means of application: pre-treatment, post-treatment and production technology. In the second group methods applied to consolidated panel are found and direct thermal treatment is the most usual one (Del Menezzi and Tomaselli, 2006). While contact post-treatments have become common practice in wet process hardboard manufacture, it is not commonly used in dry process MDF plants, but it could be introduced to impart specific properties to MDF panels. Also, post manufacture thermal treatment could decrease the moisture content of MDF panels prior to shipping, thereby reducing weight and improving their dimensional stability. Post manufacture heat-treated wood-based panels such as particleboard, waferboard, and flakeboard bonded with phenol-formaldehyde (PF) have been extensively studied.

High temperatures used in manufacturing cellulosic fiberboards and hardboards decrease the hygroscopicity of the wood fibers. Thus, the Equilibrium moisture content (EMC) of these wood fibers is lower than that of solid wood, particularly at higher humidities (Myers and McNatt, 1985).

The flexural properties of the wood based panels, static MOR and MOE, were generally affected by post heat-treatment, but this effect was strongly influenced by the exposure condition (i.e. RH) (Ayrilmis et al., 2009). The MDF panels experienced greater creep deflections at higher heat-treatment temperatures under the same environmental condition levels (Ayrilmis et al., 2009).

Heat-treated wood also exhibits lower affinity to water and a strongly modified wettability leading to important changes of its behavior with most coating or gluing processes (Petrissans et al., 2003). A wood surface, which is exposed to a high-temperature condition, can experience inactivation. Oxidation and/or pyrolysis of wood surface bonding sites are real and inevitable inactivation mechanisms at high enough temperatures and long times. A loss of hygroscopicity is assigned to a gradual loss of wood hydroxyl groups during drying. This is one of the mechanisms responsible for poor adhesion of the thermally inactivated wood. The rate of degradation is much faster at extremely high processing temperature.

During heat-treatment, physical and chemical processes occur in layers near the surface that result in a modified surface with new characteristics. After the glass transition temperature (160ºC) is achieved, plasticization of lignin starts to affect the surface characteristics of wood (Follrich et al., 2006). The heat treatment apparently resulted in such a plasticization on the MDF surfaces. High temperatures above 160 °C probably caused lignin to reach a thermoplastic condition and thus densify panel surface. Better surface quality of the heat-treated MDF can also be related to this additional surface densification on the face of the MDF panel. The surface-densified MDF samples exhibited a glossy and smooth appearance after heat treatment. Moisture in the manufactured MDF panel is transformed to steam when hot press platens contact to the panel surfaces. This steam tends to soften the fibers near the surface layers also plays a part in MDF surface compaction and plasticization which improves the surface smoothness.

Wettability is crucial for good adhesion in wood bonding. Many experiments have shown that high drying temperature reduces the wood adhesive bonding strength, or that high temperature decreases wood hygroscopicity and hinders wettability (Hakkou et al., 2005a; (Follrich et al., 2006). Wood fibers become hydrophobic after heat treatment, and their wetting capability becomes less after heat treatment (Hakkou et al., 2005a).

There is also the possibility of using color to estimate the brittleness of heat-treated wood (Phuong et al., 2007). Some darkening of the MDF specimen surfaces was observed as a result of secondary heat-treatments. The darkening on the specimen surfaces increased gradually depending on the treatment temperature ranging from 175 to 225°C. In our experience, it can be said that heat-treatment generally induced darkening. But our experience was that darkening while a somewhat weak indicator in estimating the static flexural strength of the post heat-treated MDF panels is not entirely reliable.

3. STUDIES ON THE SUBJECT AND THEIR CRITIQUE

3.1. Studies on Heat treatment of Solid Wood

Yildiz (2002) investigated that effect of heat treatment at different temperature and durations on physical, mechanical and chemical properties of spruce and beech wood. It was reported that the density observed for beech (2.25%) and spruce (1.73%) woods treated at

130°C for 2 h was higher than that of control samples. On the other hand, at longer treatment times and higher temperatures, the density decreased. The highest decrease in density was observed in samples treated at 200° for 10 h (beech, 18.37% decrease; beech spruce, 10.53% decrease). The increase in dimensional stability was found to be 50% for beech and 40% for spruce wood.

Korkut et. al. (2008) examined the effects of heat treatment on the physical properties and surface roughness of Turkish Hazel (*Corylus colurna* L.) wood. The results showed that the values of density, swelling and surface roughness decreased with increasing temperature treatment and treatment times.

Sevim et al. (2007) for red bud maple, Gunduz et al. (2008) for Camiyanı black pine investigated the effects of heat treatment on physical properties and surface roughness of wood. They found that the values of density, swelling and surface roughness decreased with increasing temperature treatment and treatment times.

Korkut et al. (2008) for Scots pine, Korkut (2008) for Uludag fir and Korkut et al. (2008) for maple wood investigated effect of heat treatment on some mechanical properties. They found that heat treatment decrease mechanical properties and increase in temperature and duration further diminished mechanical properties of the wood species.

Korkut and Hiziroglu (2009) examined the effects of heat treatment on the mechanical properties of Turkish Hazel (*Corylus colurna* L.) wood. Maximum reduction values of 68.11%, 64.97%, and 58.75% were found for Janka-hardness in radial, tangential, and tension strength parallel to grain for the samples exposed to 180ºC for 10 h, respectively. Overall results showed that treated samples had lower mechanical properties than those of the control samples.

In the another study on Spruce (*Picea abies*) wood applied heat treatment during 24 hr, weight loss was also found 0.8 % and 15.5% at 120°C and 200°C, respectively (Fengel, 1966). Zaman et al. (2000) heated Scots pine (*Pinus sylvestris*) and silver birch (*Betula pendula*) wood for 4-8 h in a steam atmosphere at low temperatures (200-230°C). They found that mass losses 6.4-10.2 and 13.5-15.2% of the initial DS at 200°C and 225°C for birch wood and 5.7-7.0 and 11.1-15.2% at 205°C and 230°C for pine wood, respectively.

Unsal and Ayrilmis (2005) found that the maximum surface roughness decrease in Turkish river red gum (*Eucalyptus camaldulensis* Dehn.) wood samples was 27.9% at 180°C for 10 h. Korkut (2008) obtained similar decreases oven-dry and air-dry density, swelling and surface roughness values for Uludag fir (*Abies bornmuellerinana* Mattf.) wood for the same treatment time and temperature.

Unsal et al. (2003) reported that in Turkish river red gum (*Eucalyptus camaldulensis* Dehn.) wood samples the largest swelling loss was at 180°C after 10 h treatment. The loss was 14.11% radially, and 21.51% tangentially. Oven-dry density decreased by up to 11.76% in the sample heat-treated at 180°C for 10 h when compared with the control samples.

Esteves et al.(2007) found that in pine (*Pinus pinaster*) and red gum (*Eucalyptus globulus*) wood samples in the absence of air by steaming, treatment inside an autoclave heated at 190–210°C for 2–12 h resulted in an equilibrium moisture content decrease by 46% for pine and 61% for eucalyptus, while the dimensional stability increased (maximum anti-shrinking efficiency in the radial direction of 57 and 90% for pine and eucalyptus, respectively) and the surface wettability was lowered. Mass losses increased with treatment time and temperature, reaching 7.3% for pine and 14.5% for eucalyptus wood. The modulus of elasticity was little affected maximum decrease of 5% for pine and 15% for eucalypt but the bending strength was reduced by 40% at 8% mass loss for pine and 50% at 9% mass loss for eucalypt wood. They found that the radial contact angle for the heat-treated pinewood increased from 40° to about 80º for a 2.5% mass loss and decreased slightly afterwards to 60°

at 7% mass loss and for eucalypt wood increased until 8% mass loss, remaining approximately constant afterwards at 75–80º until 13% mass loss.

Bengtsson et al. (2002) obtained reduction in bending strength of 50% for spruce wood and 47% for Scots pinewood treated at 220ºC. Santos (2000) found that Eucalyptus wood treated at 180°C increased in modulus of elasticity of and decreased (26%) in transverse tensile strength.

Tjeerdsma et al. (1998a) investigated that hygroscopicity (EMC), dimensional stability and modulus of rupture strength of beech and pine wood treated in a two step process mild conditions. They found that increase 39% and 35% in EMC, increase 22% and 40% in dimensional stability and decrease 3% and 20% modulus of rupture strength for beech and pine wood, respectively.

Hakkou et al. (2005a) investigated of wood wettability change during heat treatment of beech wood and found for heat treatments below 120°C, the contact angle value near from zero. After this temperature, the contact angle value changes suddenly to reach 90º for a treatment temperature between 120 and 160°C. For higher treatment temperatures, the contact angle remains constant and equal to 90º. This increase in contact angle and consequent decrease in wettability with heat treatment is in agreement with earlier data (Pecina and Paprzycki, 1988; Petrissans et al., 2003).

Shi et al. (2007) studied bending strength, modulus of elasticity, and hardness of spruce, pine, fir, poplar, and birch wood grown in Quebec. Bending strength values decreased by between 0% and 49% in all wood specimens depending on the treatment schedules applied. However, in birch wood, a slight increase was seen. Modulus of elasticity values showed decreases in spruce and pine wood specimens (between 4% and 28%); however, fir, poplar, and birch wood specimens showed increases.

Poncsak et al. (2006) studied effect of the process parameters such as maximum treatment temperature, holding time at this temperature, heating rate, and gas humidity on the mechanical properties of birch wood. They showed that mechanical properties such as the modulus of rupture and resistance against screw withdrawal decrease with increasing treatment temperature, especially above 200ºC. The hardness increases slightly with temperature above 200°C.

Stamm and Hansen (1937) reported that the hygroscopicity of black gum wood decreased to half of its original value when samples were treated at 205ºC for 6 h. In another study increases in temperature and treatment time, and also the technique used, resulted in changes in dimensional stability from 55% to 90% (Yildiz, 2002).

Kubojima et al. (2000) investigated effects of heat treatment on load deflection curve for static bending and the force-time curve for impact bending properties of spruce wood and effect of oxygen in air. Heat treatment was applied 0.5-16 h at a temperature 160°C in nitrogen gas or air. They found that the static Young's modulus, absorbed energy in impact bending and bending strength increased at the initial stage of the heat treatment and decreased later and decreases of these properties more in air than in nitrogen.

Phuong et al. (2007) investigated the brittleness of heat-treated *Styrax tonkinensis* wood. They found that heat treatment at a higher temperature or for a longer time made more brittle and the brittleness increased to four times that of the control when wood was heated at 200°C for 12 h.

Kotilainen et al. (2006) investigated water absorption differences between sapwood and heartwood of Scots pine and Norway spruce heat-treated at different temperatures. They found that the heartwood of both wood species absorbed less water than sapwood and heat-treatment evidently decreased the water absorption of spruce and pine heartwood.

Kotilainen (2000) studied changes in the chemical composition of different softwood and hardwood species, heated to temperatures between 150°C and 260°C for several hours under steam, air and nitrogen atmosphere. He found, that the reaction conditions had a clear influence on the chemical decomposition of the wood and hardwood species decomposed more extensively than softwood species. After treatment at 180°C or higher, chemical changes in lignin and hemicelluloses occur and the treated wood becomes less hydroscopic (Tjeerdsma et al., 1998b; Kotilainen, 2000).

Manninen et al. (2002) investigated the emissions of volatile organic compounds (VOCs) from air-dried Scots pine wood and from heat-treated Scots pine wood. They found that air-dried wood blocks released about 8 times more total VOCs than heat-treated (24 h at 230°C) ones. Terpenes were clearly the main compound group in the air-dried wood samples, whereas aldehydes and carboxylic acids and their esters dominated in the heat-treated wood samples.

Unsal and Candan (2007) investigated the effects of temperature and press pressure on the moisture content (MC), vertical density profile (VDP) and Janka hardness of pine wood. They found that increasing pressure and temperature was resulted in increased Janka hardness, PD and MD values which are defining factors VDP and.

Unsal et al. (2008) evaluated decay and termite resistance of thermally compressed pine wood panels at either 5 or 7 MPa and at either 120 or 150°C for one hour. They found increases in density and decreases in thickness of the panels; however, laboratory decay resistance tests using one brown rot fungus and one white rot fungus revealed that thermally compressed wood was not resistance against the fungi tested. More interesting results were found in laboratory termite resistance tests. As pressure and temperature increased up to 7 MPa and 120°C, mass losses in the specimens decreased gradually when compared to control specimens. However, the specimens compressed at 7MPa and 150°C showed higher mass losses in comparison with the specimens compressed at 7 MPa and 120°C. Decay and termite resistance of such materials is still controversial even though density is improved under thermal processing.

3.2. Studies on Heat Treatment of Wood Based Materials

Several studies have reported on the influences of the post heat-treatment of wood-based composite panels, such as particleboard, flakeboard, waferboard, and oriented strandboard (OSB) bonded with PF resin (Suchsland and Enlow, 1968; Hsu et al., 1989; Zhang et al., 1997; Ohlmeyer and Lukowsky, 2004; Del Menezzi and Tomaselli, 2006, Okino et al., 2007). These studies often reported that the secondary thermal treatment reduced swelling, enhanced resistance of the wood-based panels to moisture absorption and enhanced durability and fungal resistance of materials. However, these studies generally reported that heat treatment had embrittled wood-based panels and decreased the bending strength and the stiffness of the panels. Heat treatment has also been reported to affect a host of other moisture dependent properties (Garcia et al., 2006; Winandy and Krzysik, 2007). The treatment sometimes known as retification reduces equilibrium moisture content by permanently degrading the hemicelluloses being one of the major hygroscopic components of wood, and by volatilizing extractives or further breaking down other low-molecular weight polymers in the wood (Winandy and Krzysik, 2007). Hsu (1986) developed a fast heat-treatment process for composite panels after panel pressing. That process was based on a direct contact post treatment at temperatures between 230 and 250°C.

Tomek (1966) treated oak wood particles to heat at different temperatures (230-300°C) and different short time intervals (1-8 min) and determined a reduction of 33% in water absorption and 45-50% in thickness swelling after 24 hours of water immersion. Similar results have been found by several researchers for waferboard, low density fiberboard and fiberboard (Hsu et al., 1989; Rowell et al., 1995; Garcia et al., 2006).

Heat treatment has an impact on the mechanical properties of wood-based composites, but the results are ambiguous. Geibler (1983) found a reduction in mechanical properties of wood based composites and observed a reduction in formaldehyde emissions. Garcia et al. (2006) found no significant effect of heat treatment on the static bending properties of MDF panels produced from heat-treated fiber.

Steam pre-treatment temperatures above 200°C are very effective for improving the dimensional stability of particleboard. However, Sekino et al. (1998) reported a significant reduction of the bond strength of particleboard with steam pre-treated particles when temperatures above 200–210ºC are applied. According to Stamm (1964) this can be explained by the (partial) conversion of the polyoses, which make up about 20% of the middle lamella, into furfural polymers. This procedure was resulted in increased embrittlement and a significant reduction (up to 50%) of shear strength. This reduction in mechanical properties might limit the applications of particleboard of such a technology.

Boonstra et al. (2006) found that a two stage heat pre-treatment with temperatures below 200°C improve the dimensional stability of particleboards. The process conditions applied do have an effect on the swelling and internal bond properties of the particleboard test samples, especially during the first process stage (hydro-thermolysis). The best results were obtained with the particles which were only thermolysed (without curing).

In a previous study, equilibrium moisture contents (EMC) of the heat-treated MDF specimens exhibited a further decrease with increased exposure treatment temperature (Nadir Ayrilmis et al., 2009). Del Menezzi and Tomaselli (2006) and Winandy and Krzysik (2007) each reported that the reduction of EMC could happen because of the hemicelluloses, one of the more hygroscopic polymers within the cell wall and also generally the most heat sensitive polymers of the wood components.

In a previous study, increasing heat-treatment temperature improved thickness swelling of the MDF panels (Ayrilmis et al., 2009). However, water absorption properties were adversely affected by the heat-treatment. These results were consistent with the results obtained in previous studies (Del Menezzi and Tomaselli, 2006; Winandy and Krzysik, 2007; Mohebby and Ilbeighi, 2007). Similar results were also reported by Paul et al. (2006) for OSB made from heat-treated chips.

Stamm (1956) reported that softwood specimens heated over 30 min in air at 200°C could loose 10% of their original MOR. Loss of modulus of rupture and modulus of elasticity in heat treated wood was reported by different authors (Yildiz et al., 2006; Bengtsson et al., 2002; Kubojima et al., 2000) and heat-treated composites (Sundqvist et al., 2006; Ohlmeyer and Lukowsky, 2004; Paul et al., 2006). The loss in mechanical properties could be related to the formation of soluble acidic chemicals; such as formic acid and acetic acid, from the hemicelluloses degradation (Garrote et al., 2001; Sundqvist et al., 2006). Those acids accelerate depolymerization of the carbohydrates by breaking down the long-chain carbohydrates to shorter chains. Depolymerization and shortening of the cellulose polymer could affect MOE and MOR of wood. It is known that acidic conditions at elevated temperature can degrade wood by hydrolysis and affect the wood strength (Rowell, 2005).

In many situations where wood is subjected to applied stress and moisture content change, the wood undergoes a mechano-sorptive creep due to an interaction between stress and moisture content change. This may result in great deformation compared to constant moisture content (Zhou et al., 2000). Creep deflections in the treated MDF specimens also increased with increasing relative humidity. Researchers had previously observed that changing relative humidity above 65% resulted in a higher creep deformation in wood-based panels (Laufenberg et al., 1999; Zhou et al., 2001; Pritchard et al., 2001). During moisture cycling, the first adsorption caused an increase in the deformation compared to constant moisture content. An increase in humidity causes swelling and thereby a larger moment of inertia, which may partly compensate for the weakening of the material due to moisture uptake (Epmeier et al., 2007).

Ayrilmis et al. (2009) investigated that some physical, mechanical properties and creep deflection of post heat-treated commercial MDF panels at various temperatures and durations using a hot press. The results indicated that the post-manufacture heat-treatment of MDF panels improved thickness swelling and adversely affected water absorption and linear expansion properties and modulus of rupture and modulus of elasticity values decreased with increasing treatment temperature. Also, creep deflections of the panels increased with increasing temperature of the post heat-treatment. Furthermore, higher creep deflections of the MDF specimens exposed to the cyclic relative humidity condition could be partly caused by deterioration of the inter-particle bonding in the MDF panels. The cured PF resin between fibers in the MDF specimens is deformed by changing humidity variation; this could eventually overstress some PF bonds, resulting in less cohesion and more creep. Consequently, deterioration of the inter-particle bonding plays a role in increasing the creep deflections of the post-treated MDF specimens.

In a previous study, it was reported that post-manufacture heat-treatment was a significant factor influencing of surface roughness, wettability, and bond strength of exterior MDF panels. Heat-induced chemical modification resulted in surface inactivation of fibers in layers near the surface post-manufacture heat-treatment improved surface roughness of the exterior MDF panels (Ayrilmis and Winandy, 2009).

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