Redžo Hasanagić[1], Leila Fathi[2], Atif Hodžić[1], Mohsen Bahmani[2]*

[1]University of Bihać, Department of Wood Science and Technology, Technical Faculty, Bihać, Bosnia and Herzegovina,
[2]Shahrekord University, Department of Natural Resources and Earth Science, Shahrekord 64165478, Iran

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Physical and mechanical changes in thermal modified wood: A review

ABSTRACT

In Europe, wood is a crucial construction material that has experienced a surge in use for building applications in recent years. To enhance its dimensional stability and durability, thermal modification is a widely accepted commercial technology. Thermal modification is a popular technique that alters the properties of wood, improving its resistance to decay and increasing its dimensional stability. The process involves heating wood to high temperatures under controlled conditions, leading to chemical reactions that result in various physical and mechanical changes. This paper will discuss the effects of thermal modification on the physical properties of wood, such as density, moisture content, and color, as well as its impact on the mechanical properties, including strength, stiffness, and hardness. Additionally, the review will examine the factors that influence the degree of modification, such as temperature, duration, and wood species. Finally, the paper will conclude with an overview of the current state of research in this field and identify potential avenues for future investigation.

Keywords: *Wood, mass loss, modul of elasticity, construction, commercial, technology.*

1. INTRODUCTION

Wood is a significant building and construction material that is often utilized in outdoor settings. Its growing popularity for use in wooden facades and decking can be attributed to several factors such as low maintenance costs, broad accessibility, and simple production and processing. In addition to these benefits, wooden facades and decking have been found to have lower greenhouse gas emissions compared to other materials like brick, fibre cement, and steel [1]. Like other materials, wood used in outdoor applications is subjected to weathering and various types of degradation organisms. In temperate climate zones, fungi that inhabit wood are the primary cause for its replacement [2]. To prevent fungal decay in wood, different approaches are utilized, including the impregnation of wood with biocides, wood modification, protection by design, the selection of naturally durable wood species, and the use of hydrophobic treatments [3,4]. Wooden façades and decking can be made of untreated wood, wood treated with biocides or modified wood [5].

Choosing the right material for decking and cladding can be a difficult decision, as there are numerous options available. The selection process typically involves considering the expected lifespan and cost of the materials. However, accurately predicting the service life of wood is difficult, as it is affected by various factors such as the type of wood used, the protection measures employed, and local climate conditions [6]. Moisture content during exposure is of great interest because in addition to the material-inherent durability, the moisture and temperature conditions inside the wood, i.e., the material climate, are the most critical factors influencing the ability of fungi to decompose wood. These factors are affected by the design of the construction, the exposure conditions, and local climatic conditions (microclimate) [2,7]. The commercial production of thermally modified timber (TMT) usually takes place between temperatures of 160 and 240^{o}C. This results in a material that is darker in colour [8], has improved dimensional stability and microbial resistance compared to unmodified wood, but there is a significant reduction in strength, especially fracture resistance. The reduction in ductility makes the use of TMT problematic for many load-bearing applications [9].

*Corresponding author: Redžo Hasanagić
E-mail: redzo.hasanagic@unbi.ba
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The chemistry of thermal degradation, particularly of the lignin, is different below about 150^{o}C [10,11] and thermal modification is herein defined as being above this temperature, although irreversible changes also occur to wood heated below this temperature [12,13].

Thermal modification processes typically utilize temperatures below 240°C, as higher temperatures would cause excessive degradation of the wood, rendering the process commercially impractical. The primary drawbacks of wood, including poor dimensional stability and limited biological durability, are primarily attributed to the nature of the main polymers of the wood cell wall, which contain numerous hydroxyl groups (OH), as has been reported in previous studies [14,15]. Wood protection without toxic chemicals is the subject of numerous researches. The application of thermal modification can be considered as a solution since species with weaker properties; mainly softwood, it can be modified and transformed into completely new products with superior properties [16,17]. Thermal modification of wood is a promising technique that offers an environmentally friendly and effective way to enhance wood durability and hydrophobicity, as indicated by several studies [18-23]. The aim of this study is to present the process of thermal modification and the influence of thermal modification on the mechanical properties of wood and the impact of the processes on structural changes in wood polymers.

2. INDUSTRIAL THERMAL WOOD MODIFICATION PROCESSES

In the past few years, there have been significant advances in wood processing technologies, especially in the commercial sector, as Hill notes in his paper [24]. According to Boonstar [25] , this renewed interest is due to the declining production of durable wood, increasing demand for sustainable building materials, especially due to deforestation, and the increased introduction of restrictive regulations that reduce the use of toxic chemicals. There have been mainly five different commercial treatments: one in Finland (Thermowood), one in the Netherlands (Plato Wood), one in Germany (OHT-Oil Heat Treatment) and two in France (Bois Perdure and Rectification), as detailed in Table 1. New heat treatment processes also occur in other countries, such as Denmark Wood Treatment Technology (WTT) and Austria (Huber Holz). Some of these processes are in the implementation phase, whereas others are already in full production**.** All processes use sawn timber and processing temperature between 160 ºC and 260ºC, but differ in the conditions of the process itself, such as the presence of shielding gas nitrogen or steam, wet or dry processes, use of oil, etc. [26].

Table 1. Patented and successfully applied processes for thermal modification of wood [26]

Tabela 1. Patentirani i uspešno primenjeni procesi za termalnu modifikaciju drveta [26]

Process	Year	Initial content MC (%)	Temperature (^{o}C)	Duration of process (h)	Pressure (MPa)	Means for heat /atmosphere transfer
Plato Wood	1980	14-18	150-180/170-190	4-5	0.6-0.8	Water vapor
Thermo wood	1990	10	130/185-230/80-90	2-3	0.1	Water vapor
Le Bois procedure	1990	Fresh	200-230	12-36	0.1	Water vapor
Rectification	1997	12	160-240	8-24	-	Nitrogen atmosphere
Menz Holz	2000	10	180-220	18	-	Vegetable oil

The market for new durable modified wood products has grown significantly in recent years, especially in Europe. This increased interest depends in part on the limited use of toxic preservatives due to increased environmental concern, as well as the need for reduced maintenance of wood products that are mainly for outdoor use [12]. The change in properties after heat treatment depends on the type of wood and process conditions, in which temperature, time and absence of oxygen prevail [10]. The modulus of elasticity and flexural strength are decreasing with the increase of temperature and heat treatment time.

For example, during heat treatment at temperatures between 170°C and 200°C and for different treatment times, it has been found that the reduction of the pine elasticity model is less than 5 % until a mass loss of 4% is achieved, and then increases rapidly and reaches up to 16% with a mass loss of 6 % [13]. The reduction in mechanical properties due to thermal modification can be mitigated by wood samples, as has been reported in several research papers [27]. Wood compression is a process used to increase the density of wood and improve its mechanical properties without chemical additives, according to Laine et al. in research [14], which provides new materials and functionality [15].

Wood modification processes affect the previously described conditions of wood exploitation, in a desirable or undesirable manner, such as filling the lumen of wood with chemical substances, without changing the walls of wood cells. The cell wall is filled by filling the cavities in the cell, thus blocking the waterways. An example of filling is treatment with resins, which is very difficulty to react with wood. Since almost no molecular change in wood is achieved, the filling is not considered as modification of the wood.

Wood modification is a method in which the cell wall polymers of the molecular structure of cell wall polymers (cellulose, hemicellulose and lignin) are changed. Similary, when it comes to thermal modification of wood, cell wall polymers are altered. This treatment can lead to crosslinking, reduction of OH groups and (unwanted) chain cleavage. Reduction of available OH groups leads to limited interaction with water in relation to untreated wood. The structure of the cell wall of wood mainly consists of cellulose, hemicellulose and lignin. All of these components contain free hydroxyl groups. These hydroxyl groups play a key role in the interaction between water and wood. At the same time these groups are the most reactive places. If the wood is exposed to humid conditions, water molecules accumulate between the wood polymers and form hydrogen bonds between the hydroxyl groups and the individual water molecules. This water needs space between the components of the cell wall, which leads to swelling of the tree, and fungi and insects infestation (Figure 1.). The wood industry is continuously developing advanced processes, materials and solutions to meet the requirements and increase market competitiveness. One such treatment that occurs is thermal modification of wood, which involves heating wood at high temperatures and low oxygen levels to improve its properties, such as color, durability, and dimensional stability [9]. Thermal modification can reduce the hygroscopicity of wood, which is the tendency of wood to absorb and release moisture from the environment. This can result in lower equilibrium moisture content and lower shrinkage and swelling of wood. Thermal modification can also enhance the resistance of wood to fungal decay and weathering. Thermal modification can be applied to different types of wood species and products, such as solid wood, veneer, plywood, particleboard, and fiberboard.

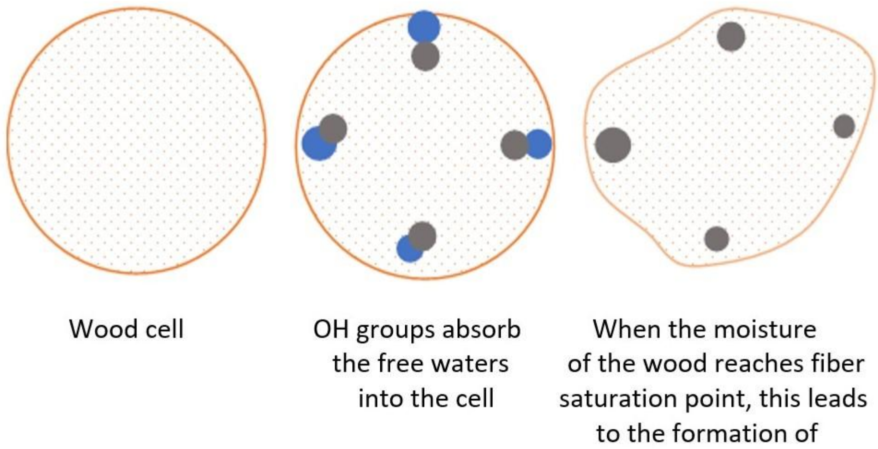

Figure. 1. Moisture absorption into wood

Slika 1. Upijanje vlage u drvo

Thermal modification is a process that involves subjecting wood to controlled high temperatures using only water vapor, fresh water, and heat. No chemical preparations or additives are used during the process, making it highly environmentally friendly. The treatment is performed in specially designed chambers that are equipped with a fully automated process control system and operate at temperatures ranging from 160°C to 260°C. The use of high temperature, pressure, and water vapor significantly improves the quality of the wood and its physical and mechanical properties.

Several important parameters influence the properties of the thermally modified wood. These include the type of heating medium, the duration of the process, the final temperature, the wood's moisture content before heating, and the type of wood being treated.

During the process of thermal modification, the moisture content of the wood is typically reduced by up to 1%, and the wood's color often becomes uniformly darker. Although thermally modified wood is not as prevalent on the market, certain wood types such as beech and ash are becoming increasingly popular among customers.

Thermal modification of wood offers several benefits, such as reduced moisture absorption, dimensional stability, increased biological resistance and insulating properties, and an even change in color to darker tones throughout the cross-section. The resulting wood is of higher quality and is particularly suitable for varnishing. Additionally, thermal modification achieves other positive improvements such as water impermeability, resistance to acids and bases, UV resistance, and enhanced mechanical and thermal properties.

When subjected to high pressure, solid wood becomes denser and less porous, which improves its mechanical properties without significantly increasing its weight. As a result, compression processes are increasingly being used in the processing of veneers and small wood slats, to which various resinous additives are added to enhance adhesion.

3. CHANGES IN THERMALLY TREATED WOOD

Heat treatment significantly affects the properties of wood, e.g. hygroscopicity and dimensional stability, resistance to biotic agents, mechanical properties, properties such as color, odor, adhesiveness and coating performance (Table 2).

Table 2. Main changes in properties of heat-treated wood compared to untreated wood [28]

Tabela 2. Glavne promene u svojstvima termički obrađenog drveta u poređenju sa neobrađenim drvetom [28]

Desirable change	Undesirable change
Increased dimensional stability	Decreased impact strength
Increased resistance to decay	Increased brittleness
Lower thermal conductivity	Reduced hardness
Lower density	Longer processing time for gluing
Dark brown color	-
Characteristic scent	-

A common effect of the heat treatment process is a loss of wood mass, which can reach up to 20% depending on the specific process used. The properties of thermally modified wood (TMW) are largely influenced by the intensity of the heat treatment, including the temperature and duration of the process, in addition to the properties of the original wood material. As many mechanical properties of wood, such as hardness, elasticity, and abrasion resistance, are correlated with density, increasing the density of TMW through heat treatment can lead to improvements in these properties. For this reason, considerable efforts have been made to develop effective heat treatment processes for wood.

4. PHYSICAL CHANGES OF WOOD CAUSED BY THERMAL MODIFICATION

Color change

As mentioned above, Thermally modified wood (TMW) is becoming increasingly popular due to its improved properties such as dimensional stability, decay resistance, and improved color. One of the most notable changes that occur in TMW is its color change. This color change is a result of a complex chemical reaction that occurs during the thermal modification process. The color change observed in TMW can range from a slight yellowing to a deep brown/red color. The color change of thermally modified wood is mainly caused by the thermal degradation of the main chemical components of wood, such as cellulose, hemicellulose, lignin, and extractives. The extent and mechanism of the degradation depend on the temperature, duration, and atmosphere of the thermal modification process. Generally, higher temperature and longer duration result in more degradation and darker coloration of wood. The atmosphere can also affect the color change by influencing the oxidation and hydrolysis reactions of wood components. For example, thermal modification under wet conditions (cell wall contains moisture) can result in more degradation of hemicelluloses and extractives than under dry conditions (cell wall at nearly zero moisture content). Several studies have investigated the color change of thermally modified wood using different methods, temperatures, durations, atmospheres, and wood species. Qu *et al.* [29] studied the color change of poplar (*Populus euramericana* cv.) wood modified by pretreatment with aluminum sulfate vacuum impregnation and thermal modification at 180 °C for 4 h. They found that the pretreatment improved the color stabilization of thermally modified wood by preventing the photooxidative degradation of lignin and extractives. The L* value decreased by 19%, while the a* and b* values increased by 17% and 11%, respectively. The ΔE* value was 22.5 for the pretreated-thermally modified samples compared to 30.8 for the thermally modified samples after artificial weathering for 144 h. Hrčková *et al.* [30] studied the effect of thermal modification temperature on the color change of spruce (*Picea abies*) and oak (*Quercus robur*) wood. They found that the L* value decreased with increasing temperature from 160 to 210°C for both species. The a* value increased for spruce but decreased for oak with increasing temperature. The b* value increased for both species with increasing temperature. The ∆E* value reached its maximum at 210°C for both species. Li *et al*. [31] studied the color change of Chinese fir (*Cunninghamia lanceolata*) wood modified by mild hydrothermal treatment at different temperatures (120-180°C) and durations (1-5 h). They found that the L* value decreased with increasing temperature and duration for both radial and tangential sections. The a* value increased with increasing temperature but decreased with increasing duration for both sections. The b* value increased with increasing temperature and duration for both sections. The ∆E* value increased with increasing temperature and duration for both sections. These studies show that color change in thermally modified wood is a complex phenomenon that is influenced by various factors related to the thermal modification process and wood properties.

Mass loss and change in crystallinity

Mass loss in wood is one of the most important characteristics of heat treatment and is usually called a quality indicator. Several authors investigated the mass loss by thermal modification and concluded that it depends on the type of wood, heating medium, temperature and processing time (Figure 2).

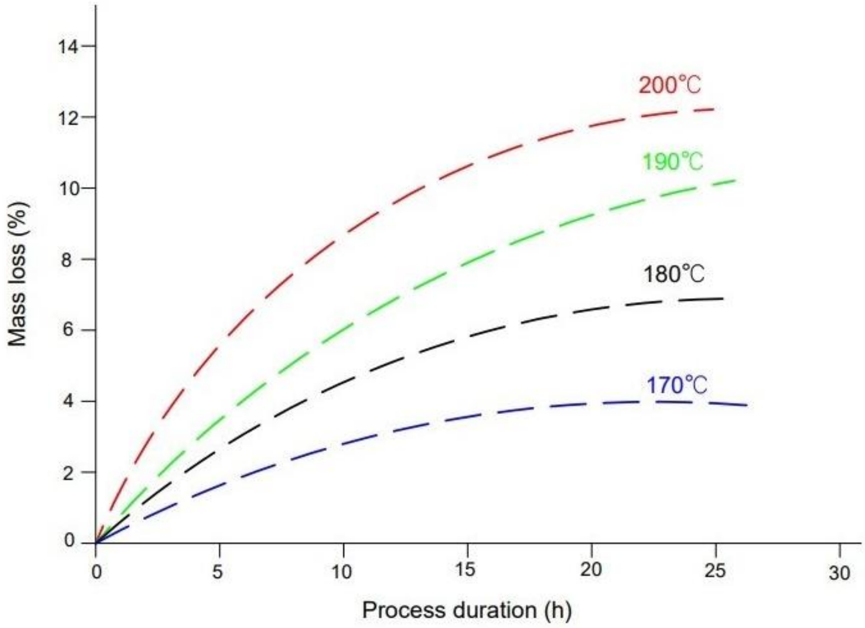

Figure 2. Loss of wood mass by the action of temperature and processing time [16]

Slika 2. Gubitak mase drveta dejstvom temperature i vremena obrade [16]

Thermal modification of wood causes a reduction in its mass and volume, with the extent of reduction depending on the specific method of treatment, as well as the temperature and duration of exposure. Weight percentage loss (WPL) is a measure of the mass loss of wood due to thermal modification, which is a process that involves heating wood at high temperatures (160-240°C) and low oxygen levels to improve its properties, such as durability, dimensional stability, and hygroscopicity. WPL can indicate the extent and mechanism of the thermal degradation of the main chemical components of wood, such as cellulose, hemicellulose, lignin, and extractives. WPL can also affect the physical and mechanical properties of wood, such as density, strength, stiffness, and hardness. WPL is mainly caused by the thermal decomposition and volatilization of wood components, which can result in the formation of water, carbon dioxide, carbon monoxide, methane, acetic acid, formic acid, furfural, and other organic compounds. The rate and degree of the decomposition and volatilization depend on the temperature, duration, and atmosphere of the thermal modification process. Generally, higher temperature and longer duration result in more WPL of wood. The atmosphere can also affect the WPL by influencing the oxidation and hydrolysis reactions of wood components. For example, thermal modification under wet conditions (cell wall contains moisture) can result in more WPL than under dry conditions (cell wall at nearly zero moisture content). WPL can be measured by various methods, such as gravimetric analysis, thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS). Several studies have investigated the WPL of thermally modified wood using different methods, temperatures, durations, atmospheres, and wood species. Li et al. [31] studied the WPL of poplar (*Populus euramericana* cv.) wood modified by pretreatment with aluminum sulfate vacuum impregnation and thermal modification at 180°C for 4 h. They found that the pretreatment reduced the WPL of thermally modified wood by inhibiting the thermal degradation of hemicellulose and extractives. The WPL was 8.6% for the pretreated-thermally modified samples compared to 10.9% for the thermally modified samples. Hill *et al.* [32] reviewed the current state of knowledge regarding the chemical changes and hygroscopicity of thermally modified wood modified under dry and wet conditions. They discussed the relationship between WPL and mass loss kinetics under different conditions. They also highlighted that wet-modified wood exhibits behavior that changes when subjected to water leaching post-treatment, which includes further WPL. Hrčková, et al. [30] studied the effect of thermal modification temperature on the WPL of spruce (Picea abies) and oak (Quercus robur) wood. They found that the WPL increased with increasing temperature from 160 to 210°C for both species. The WPL reached its maximum at 210°C for both species. Presley *et al.* [33] studied the durability of thermally modified western hemlock (*Tsuga heterophylla*) lumber against wood decay fungi using a soil block test method. They found that thermally modified western hemlock showed an overall average WPL of 41.2% across all test fungi after 16 weeks. They also found that brown rot fungi caused much higher WPL than white rot fungus.

Certain material losses from the cell lead to changes in the dimensions of the wood, which can cause particular geometric changes in larger workpieces, in case the process does not have adequate conditions. As a result of mass loss, the specific weight of wood decreases with increased time and temperature, but the changes that occur depend on the relationship between mass loss and volume change. Hardwood usually loses more mass than softwood.

The data are difficult to compare because different treatment procedures, time, temperature, types, and initial moisture content were used. In paper [16] with pine and birch treated between 200°C and 230°C for 4h and 8h, it was determined that the mass losses for pine are lower than for birch: mass loss for pine varied between 5.7 % (4h) and 7.0 % (8h) at 205°C and between 11.1 % (4h) and 15.2 % (8h) at 230°C, whereas mass loss for birch varied between 6.4 % (4h) and 10.2 % (8h) at 200°C and between 13.5% (4h) and 15.2 % (8h) at 220ºC.

In research [18] and [34] the mass loss of spruce wood samples at 180°C and 225°C in the time interval 4-8h and obtained results of 1.5 % at 180°C (4h) and 12.5% at 225°C (6h). Study [35] compared mass losses with heat treatment in air and in the atmosphere with water vapor, using pine wood at 160°C, 190°C and 220°C for 6h and 24h, and confirmed that mass losses in the presence of air and water vapor for 6 hours were similar, while mass losses in the air were higher for 24h, especially for wood treated at 190°C and 220°C. In the reported [36] a higher mass loss for hardwood (*Eucalyptus globulus*) than for softwood (*Pinus pinaster*) under the same treatment conditions. At the beginning of the process of thermal modification of wood, the degree of crystallinity increases, and as the heat treatment time lengthens, cellulose decomposes with a constant decrease in crystallinity.

In the paper written by [37], they evaluate the influence of heat treatment temperature and mass loss on the shear strength of spruce samples glued with phenol-formaldehyde (FF) and urea-formaldehyde (UF) adhesives, which were previously thermally modified. The results of this research have shown that heat treatment caused mass loss of treated wood. On the other hand, the shear strength of FF and UF adhesive bonds was not significantly reduced compared to untreated wood. Immersion of the samples in water led to a decrease in shear strength by about 40-50 %. A significant decrease in shear strength was also observed in cooked samples. Such decrease in the shear strength of the samples glued with FF adhesive was much larger after boiling the water, while most of the samples bound with UF adhesive disintegrated.

5. MECHANICAL PROPERTIES

Strength and resistance

The authors in paper [38] report of decrease in strength, resistance and abrasion resistance during the processing wood at high temperatures. The loss of strength depends a lot on the type of heat treatment used. The loss of strength occurs faster in closed systems than in open ones, in hygrothermal conditions compared to hydrothermal conditions, and during processing in a chamber with the presence of air as opposed to that without the presence of air. Hardwood loses more strength than softwood when the process is monitored under the same conditions [27].

Modulus of elasticity

Research has shown that there is a slight increase in the modulus of elasticity when wood is heat treated for a shorter time. The reduction in modulus of elasticity occurs when the rate and magnitude of the reduction depending on temperatures and other processing conditions.

Most mechanical tests of thermally modified wood are conducted on relatively small specimens where advantages and disadvantages, such as bumps, can be eliminated. Therefore, they have limitations in the use of heat-treated wood in real-life situations. In paper [22], the authors studied the behavior of large spruce and pine beams that were hydrothermally treated at 220°C and concluded that there was a decrease in flexural strength of 50 % and a small reduction of the modulus of elasticity. An increase in scattering results was observed compared to untreated wood, and all tests showed the fragility of thermally modified wood in the fracture mode.

Modified beech wood impregnated with a nanosuspension of silver and examined their relationship to cellulose crystallinity [39]. They concluded that increased crystallinity and crosslinking of lignin can compensate for some reduced properties caused by thermal modification, but this significantly depends on the temperature used in the process. Physical properties and mechanical properties (MOR and MOE) of treated wood showed statistically insignificant changes at low and high temperatures compared to control samples.

In an attempt to assess the effects of heat treatment on wood cell walls, pine wood (*lat. Pinus massoniana Lamb*) was thermally modified at 150, 170, and 190 °C for 2, 4, and 6 hours, respectively. The modulus of elasticity and hardness of thermally modified wood were reduced along with a decrease in the creep ratio of the cell walls. However, treatment at 190°C/6h can adversely affect the mechanical properties of cell walls, causing partial degradation of hemicelluloses and cellulose, according to [40].

The modulus of elasticity (MOE) and the modulus of rupture (MOR) were measured in paper [41]. The results have shown that the modification in the closed system, especially at high pressure, indicates differences in the chemical structure between the modified wood and the modification in the open system. In both systems, MOR showed a better association with chemical changes than MOE, especially xylose, cellulose DP, lignin, and total phenols. Such analyzes suggest the tendency of brittle wood in closed system modifications at high pressure, rather than in open system modifications.

Modulus of rupture

Unlike the modulus of elasticity, in wood that is thermally modified, there is no increase in the modulus of rupture, even in the shortest period of time. Dinwoodie in research [42] states that the reason is the fact that modulus of rupture is actually equal to the stress in the fibers at the moment of rupture and as such is bound to the ultimate flexural strength. As with other physical properties of thermally modified wood, the reduction of the modulus of rupture is a function of the processing conditions.

In research [43] state that there is a greater reduction in modulus of rupture when wet wood samples are thermally modified in the presence of air, compared to heating wood dried in an oven. It was also concluded that there is a significant reduction in the modulus of rupture even when the samples are heated at low temperatures such as 120 ºC, for extended periods of time.

The influence of different thermal modification temperatures of 160°C, 180°C and 210°C on changes in basic chemical components of wood and the effect of these changes in wood on flexural strength of European oak and spruce can be compared to unmodified wood. During the thermal modification, the flexural strength initially increased in both types of wood at a temperature of 160 °C, but decreased at higher temperatures. The largest decrease in flexural strength was recorded at a temperature of 210°C and was about 32.2% for oak and 39.8% for spruce. Thermal modification caused an increase in the relative content of extracts, lignin and cellulose, but the relative content of hemicelluloses in wood was lower due to the increase in thermal modification temperature. [44]

Dimensional stability

The main disadvantages of wood, dimensional stability and biological durability, are mainly due to the nature of the main polymers of the cell wall of wood, especially due to the large number of hydroxyl groups (OH), as reported in studies [14,15]. The protection of wood without toxic chemicals has been the subject of numerous studies. The application of chemical or thermal modification can be considered a solution to this, since species of inferior properties, mainly softwood, can be modified and transformed into completely new products with superior properties [16,45].

The increase in dimensional stability occurs during thermal modification, but the effect depends on the process parameters. In paper [46], authors state that the improvement of dimensional stability of softwood increases with increasing temperature and processing time. For example, an improvement in dimensional stability of 20% can be achieved by heating smaller wood samples at 150ºC for 6 days, or at 250ºC for 3 minutes. There are conclusions that heating dry wood at temperatures of 165ºC to 205ºC for 6 hours significantly reduces the improvement of dimensional stability, but there were no changes when the wood was heated in the presence of water. The presence of water was thought to suppress those thermal reactions that involved water loss in the structure itself. When heated in air, there was a greater reduction in the improvement in dimensional stability compared to heating in a reduced atmosphere [9].

In paper [47] authors concluded that the change in dimensional stability largely depends on the processing atmosphere used. They heated wood samples in air or nitrogen at 300°C and concluded that dimensional stability reached its highest value at approximately 20 % mass loss. Through this loss of mass, a further increase in dimensional stability is achieved only when the wood is heated in a closed system. Dimensional stability did not change when the thermal mass loss exceeded 20 % when samples were heated in the open nitrogen systems, whereas there was a decrease in efficiency when the samples were heated in an open system in the presence of air. In addition, it was determined that the swelling of the heat-treated wood in the concentrated aqueous solution of sodium hydroxide, morpholine or pyridine was the same or greater than that occurring in the unmodified control samples, with only the swelling in the water being reduced. This data provided the conclusion that the increased dimensional stability did not occur due to the formation of cross-links of the ether during heat treatment. However, the methods used in this study proved to be harsh compared to the latest heat treatment methods, and the possibility of cross-linking in lignin cannot be excluded as at least one parameter contributes to increased dimensional stability of thermally modified wood.

Burmester in paper [48] considered that the loss of hemicellulose is the main contribution to the dimensional stability of heat-treated wood. Keith and Chang in their [49] state that improvements in dimensional stability, as a result of heat treatment, depending on wood species and that they are more noticeable in the radial direction which is attributed to anatomical differences. In paper [50], authors studied the changes in dimensional stability during wood heating and concluded that a linear interdependence is obtained in the change of properties when entered according to the square root of the heating time. One of the challenges with thermally modified wood is that it can have a tendency to shrink excessively during the thermal modification process, which can lead to warping and cracking. Anti Shrinking Efficiency (ASE) measures the effectiveness of different thermal modification processes in minimizing wood shrinkage. Different methods of thermal modification can affect the ASE of wood differently. In study [51] compared the ASE of beech wood modified by mild hydrothermal treatment at different temperatures (120-180°C) and durations (1-5 h). They found that the ASE increased with increasing temperature and duration, but decreased at high temperature (180 °C) and long duration (5 h). The optimal conditions for achieving the highest ASE were 140-160°C and 3 h. The ASE values ranged from -20% to 60% for anti-shrinkage efficiency (ASE-1) and from -6% to 50% for anti-swelling efficiency (ASE-2). Another study by Sargent [52] evaluated the ASE of radiata pine (*Pinus radiata*) modified by acetylation, furfurylation, or thermal modification using four different tests: soaking in water until maximum swelling, swelling rate in water, long-term swelling in humid air, and short-term swelling in humid air. They found that all the modified samples had higher ASE than the unmodified controls in all the tests, but the relative performance of the different modifications varied depending on the test conditions. For example, soaking in water showed no difference between thermally modified and furfurylated samples, but swelling rate showed that furfurylated samples swelled very slowly. Long-term swelling in humid air showed that thermally modified samples had higher ASE than furfurylated samples, but short-term swelling showed no difference between them. A review by Mendis *et al.* [53] evaluated the current methods for measuring dimensional stability in solid wood, including ASE tests. They discussed the advantages and disadvantages of different methods and suggested some improvements for standardization and accuracy. They also highlighted the importance of considering factors such as moisture sorption kinetics, hysteresis effects, and cell wall structure when interpreting ASE results. These studies show that ASE is a useful indicator of dimensional stability in thermally modified wood, but it can vary depending on the method of modification, the moisture condition, and the direction of wood grain. Therefore, it is important to use multiple tests and compare different types of modified wood to obtain a comprehensive understanding of their dimensional stability behavior.

Biotic persistence of thermally modified wood

Heat treatment improves the resistance to decay of modified wood due to biological attack. As with other properties, there are differences in quality depending on the method of processing and the type of testing. The mechanism of improved resistance to decay has not yet been established, although this is undoubtedly associated with a loss of polysaccharide content and a reduced amount of water content in the cell wall. The loss of OH groups from the cell wall polymer components can also affect the resistance to decay of thermal wood. The possibility of the formation of biocidal chemical compounds in wood during heating should also be considered. Samples of different wood species were treated with water vapor at 150°C or heated in an air oven at 150°C at different time periods, and were exposed to the attack of insects *C. Formosanus* or *R. Speratus*. Heat treatment in a water vapor atmosphere had the effect of inducing attacks on treated wood samples, while dry heating had little effect. [9]. Several authors have reported increased resistance to rot for different wood species. In their study, [50] studied the effect of heat treatment of wood at temperatures between 200°C and 260°C on three less resistant species (spruce, fir and poplar) on resistance to several fungi (*Coriolus versicolor*-white rot, *Gloeophyllum trabeum* and Coniophora puteana-brown rot). In all cases, the mass loss of treated wood was below 1%, while for untreated sample it was greater than 40%. For heat treatment of pine (*Pinus sylvestris*) for 6-24 h at 160°C, 190°C and 220°C, [35] they found mass losses of less than 3% only for treatment at 220 °C and 24 h, 1.3% for *Coniophora puteana* (39.8 % in control samples (C)), 1.6% for *Gloeophyllum trabeum* (22.0% (C)), 2.2 % for *Poria placenta* (48.5% (C)) and 3.0% for *Coriolus versicolor* (11.6% (C)).

Thermal modification does not significantly improve resistance to rot when wood touches the ground. In studied [50] the loss of mass in contact with the soil due to several species of pine rot (*Pinus pinaster*) treated at temperatures from 200 °C to 260°C. They concluded that in relation to brown rot (*G. trabeum*) there was a significant improvement from 57% to 11% mass loss, as compared to *Poria placenta* where mass loss decreased from 54% to only 47% and *I. lacteus* with mass loss from 35% to 28%. In paper [54], the authors analyzed extracts of treated pine and poplar wood and identified some toxic aromatic compounds derived from phenantrene and acenaptylene. However, the increased resistance to rot in the analyses [55] is not a consequence of new substances formed during processing, because the differences in the resistance of wood separated by water and acetone and unused wood were very small. There are also reports that thermal modification of wood is a suitable and very environmentally friendly method that increases durability and hydrophobicity [18].

The hygroscopicity of wood is markedly reduced as a result of thermal modification. The reduction is a result related to the time and temperature of the process, and the processing atmosphere used during the process. These parameters also affect the sorption behavior of thermally modified wood. Decreases in water sorption capacity are associated with a decrease in hydroxyl groups within the wood wall as a result of hemicellulose degradation. In paper [56], the researchers discovered that the equilibrium moisture content at 90 % of the relative humidity of thermally modified pine wood at 300^0C decreased in relation to untreated wood to a 1-hour treatment, but then increased for the duration process. When heating is performed under nitrogen, the sorption is constant up to a heating time of 60 minutes or more. Rusche in paper [58] discovered that the sorption capacity of wood samples decreases as processing time and temperature increase. However, when the thermal process of the treated samples was at a temperature of 200°C, the sorption capacity began to increase again with extended heating periods (24 hours for beech and 48 hours for spruce), corresponding to a heat loss of about 20%. In most studies, the sorption behavior was determined using a limited number of relative humidity values, and the change in the shape of the desorption isotherm is not obvious. It is much more acceptable when sorption and desorption data are recorded using a higher number of relative humidity measurements. In paper [58], the reduction of the saturation point of wood fibers subjected to heat treatment was determined, using a differential scanning calori-meter. The decrease in the fiber saturation point showed a good correlation with the decrease in swelling. Surface humidity of thermally modified wood decreases due to a decrease in the content of hydroxyl groups in the modified wood, the authors state in their study [60]. Thermally modified wood has improved durability, but does not meet expectations in humid conditions, according to paper [61] Spruce samples were treated with a suspension of natural wax to reduce water intake. The impregnated samples were later thermally modified at 185, 200, 215 and 230°C. The results of this study showed that the combination of wax treatment and thermal modification effectively improves hydrophobicity, reduces liquid water intake, slows water vapor uptake, and improves resistance to fungal decay of treated materials.

6. CHALLENGES AND OPPORTUNITIES IN HEAT-TREATED WOOD

Heat-treated wood faces some challenges and limitations that need to be addressed and overcome. One of the main challenges is the reduction in strength and stiffness of heat-treated wood due to the thermal degradation of wood components, especially hemicellulose and lignin. The loss of strength and stiffness can affect the load-bearing capacity and performance of heat-treated wood products, especially under dynamic or impact loading. Therefore, heat-treated wood is not recommended for structural applications where high strength and stiffness are required. Another challenge is the quality control and standardization of heat treatment processes and products. Different methods and conditions of heat treatment can result in different properties and performance of heat-treated wood. For example, the temperature, duration, and atmosphere of heat treatment can affect the extent and mechanism of thermal degradation, color change, weight loss, dimensionnal stability, and durability of heat-treated wood. Therefore, it is important to establish clear specifications and standards for heat treatment processes and products to ensure consistency and reliability. A third challenge is the environmental impact and sustainability of heat treatment processes and products. Heat treatment consumes energy and emits greenhouse gases during the heating process. Heat treatment also reduces the biodegradability and recyclability of wood due to the formation of thermally stable compounds in the wood structure. Therefore, it is important to evaluate the life cycle assessment and carbon footprint of heat treatment processes and products to ensure their environmental friendliness and sustainability. Despite these challenges, heat-treated wood also offers some opportunities and advantages that can be explored and exploited. One of the opportunities is the development of new products and applications based on heat-treated wood. For example, heat-treated wood can be combined with other materials, such as metals, plastics, or composites, to create novel hybrid products with enhanced properties and functionnality. Heat-treated wood can also be used for innovative applications, such as smart materials, sensors, actuators, or energy storage devices. Another opportunity is the optimization and improvement of heat treatment processes and products. For example, heat treatment can be modified or combined with other treatments, such as chemical modification or impregnation, to achieve better properties and performance of heat-treated wood. Heat treatment can also be tailored or customized to suit different types of wood species and products according to their specific requirements and preferences. A third opportunity is the promotion and dissemination of heat treatment technology and knowledge. For example, heat treatment can be integrated into education and training programs to increase the awareness and understanding of heat treatment among students, researchers, professionals, and consumers. Heat treatment can also be supported by policy and regulation frameworks to facilitate its adoption and implementation in different sectors and regions. The modified wood should not be toxic during use, and its disposal at the end of its life should not result in any toxic residues. Thermal modification is a modern solution that has gained popularity in the last few decades. It involves the use of heat treatment to modify the properties of wood, including its physical-mechanical properties, and has been used to improve the performance of structural joints. Numerous studies have been conducted on the heat treatment of wood, including its equilibrium humidity, dimensional stability, durability, and mechanical properties. The mass loss, humidity, color, chemical transformation, quality control, and modeling have also been extensively studied. The interest in heat treatment of wood, improvement of its properties, and quality control is significant and increasing.

7. CONCLUSIONS

Thermal modification of wood is an innovative technique that can enhance the performance and durability of wood products for various applications. By exposing wood to high temperatures and low oxygen levels, thermal modification can alter the chemical and physical properties of wood, such as reducing its hygroscopicity, increasing its dimensional stability, improving its thermal insulation, and enhancing its resistance to biodegradation and insect infestation. These benefits can extend the service life of wood products and reduce the maintenance costs. Moreover, thermal modification is an environmentally friendly technique that does not involve the use of toxic chemicals or generate harmful emissions. The increased durability of thermally modified wood can also contribute to the sustainable management of forest resources by reducing the demand for raw wood materials and promoting the use of fast-growing and low-value wood species. Therefore, thermal modification of wood is a promising technology that can address the global challenges of wood utilization and environmental protection. It is worth noting that thermal treatment of wood has gained worldwide recognition as a trend to enhance its properties. Therefore, manufacturers worldwide should increasingly adopt this process to prevent the excessive depletion of forest resources and environmental degradation.

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IZVOD

FIZIČKE I MEHANIČKE PROMENE U TERMO MODIFIKOVANOM DRVETU: PREGLED

U Europi je drvo ključni građevinski materijal koji je posljednjih godina doživio porast upotrebe u građevinarstvu. Kako bi se poboljšala njegova dimenzionalna stabilnost i trajnost, toplinska modifikacija široko je prihvaćena komercijalna tehnologija. Toplinska modifikacija je popularna tehnika koja mijenja svojstva drveta, poboljšavajući njegovu otpornost na propadanje i povećavajući njegovu dimenzijsku stabilnost. Proces uključuje zagrijavanje drveta na visoke temperature u kontroliranim uvjetima, što dovodi do hemijskih reakcija koje rezultiraju raznim fizičkim i mehaničkim promjenama. U ovom će se radu raspravljati o učincima toplinske modifikacije na fizikalna svojstva drveta, kao što su gustoća, sadržaj vlage i boja, kao i njezin utjecaj na mehanička svojstva, uključujući čvrstoću, krutost i tvrdoću. Dodatno, pregled će ispitati faktore koji utječu na stepen modifikacije, kao što su temperatura, trajanje i vrsta drveta. Na kraju, rad će zaključiti pregledom trenutnog stanja istraživanja u ovom području i identificirati potencijalne puteve za buduća istraživanja.

Ključne reči: *Drvo, gubitak mase, modul elastičnosti, gradnja, komercijalna, tehnologija.*

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