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The Influence of Thermal Modification on Selected Wood Properties

Vplyv termickej modifikácie na vybrané vlastnosti dreva

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Review

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Abstract

The interest in the thermal modification of wood has been increasing in the last decades. The interest may be induced by various reasons, for example declining production of durable timber, an increasing demand for sustainable building materials, deforestation of especially subtropical forests, or increased introduction of governmental restrictive regulations reducing the use of toxic chemicals. This study focuses on the changes in wood properties caused by the temperature. Literature recherche was conducted in this review. There are investigated properties such as mass loss, chemical composition, mechanical properties, optical properties, surface quality and fire-technical characteristics. Most of the mentioned properties have been investigated thoroughly by many authors, but the research regarding fire properties of thermally modified wood is scarce. This review gives reader a view on the influence of the thermal modification on selected wood properties.

Keywords: thermal modification; mass loss; chemical composition, mechanical properties, fire-technical characteristics

1 Introduction

Wood is also used as an engineering and structural material. Unprotected wood after exposing to outdoor conditions undergoes a variety of degradation reactions caused by diverse environmental factors such as light, moisture, heat, oxygen, pollutants, pests, etc. [1-3]. There are various ways to protect the wooden parts of buildings, e.g. nano-metal impregnation [4], insecticide treatments [5], fungal metabolites [6], and thermal modification [7].

The thermal modification has been used to improve the properties of wood for nearly a century [8]. The advantage of the thermal modification is that the environmental impact of

1 Úvod

Drevo sa používa aj ako stavebný a konštrukčný materiál. Nechránené drevo po vystavení vonkajším podmienkam podlieha rôznym degradačným reakciám spôsobeným rôznymi faktormi životného prostredia, ako je svetlo, vlhkosť, teplo, kyslík, znečisťujúce látky, škodcovia atď. [1-3]. Existujú rôzne spôsoby ochrany drevených častí budov, napr. impregnácia kovovými nanočasticami [4], insekticídne ošetrenia [5], metabolitmi húb [6] a termickou modifikáciou [7].

Termická modifikácia sa na zlepšenie vlastností dreva používa už takmer sto rokov [8]. Jej výhoda spočíva najmä v malom nepriaznivom dopade na životné prostredie [9].

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this process is low [9]. Heat is introduced into the treatment system and smoke released from wood during the thermal degradation can be retrieved, condensed and purified [10]. At the end of its lifecycle, heat treated wood can be recycled without detrimental impact on the environment to the contrary of chemically treated wood impregnated with biocidal active ingredients [11]. It is also held that the environmental credentials of thermally modified wood in terms of ecotoxicity are superior to that of untreated wood and may surpass those of several man-made materials [12]. Among positive changes in thermally modified wood are improved decay resistance [13-15], dimensional stability [16], surface hardness [17, 18], lower equilibrium moisture content [19, 20], and darker decorative colour [21-23].

The disadvantage of thermally modified wood is in deterioration of some of the mechanical properties such as: bending and compression strengths [24, 25], stiffness and shear strength [17], modulus of rupture and modulus of elasticity [7, 26], as well as the mass loss [19, 27].

2 Mass Loss

Mass loss depends on wood species, heating medium, temperature, and treatment time.

Kačíková *et al.* [28] treated Norway spruce wood at the temperature range of 113 °C – 271 °C. They found, that the mass loss increased with the temperature of the treatment, for example, the mass loss at the temperature of 158 °C was 1.53%, and at the temperature of 271 °C, it was 32.97%.

González-Pena *et al.* [29] investigated changes in beech (*Fagus sylvatica*), Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) wood after the thermal modification at the temperature range of 190 °C – 245 °C at five treatment times (0.33 h, 1 h, 4 h, 8 h and 16 h). Beech specimens exhibited higher mass loss than softwoods at equivalent periods of treatment regardless of the exposure temperature; for the beech wood the mass loss varied between 0.3% (0.33 h) and 6.7% (16 h) at 190 °C, and between 12.2% (0.33 h) and 27.0% (16 h) at 245 °C, for the pinewood between 0.6% (0.33 h) and 4.5% (16 h) at 190 ºC and between 5.6% (0.33 h) and 21.5% (16 h) at 245 ºC, and for the spruce wood between 1.1% (0.33 h) and 3.6% (16 h)

Do systému sa pri termickej modifikácii dodáva teplo a uvoľnené plynné produkty tepelnej degradácie sa môžu získavať, kondenzovať a čistiť [10]. Na konci svojho životného cyklu môže byť tepelne ošetrené drevo recyklované bez nepriaznivého vplyvu na životné prostredie na rozdiel od chemicky upraveného dreva, ktoré bolo impregnované biocídnymi látkami [11]. Okrem toho je tepelne modifikované drevo vhodnejšie aj z hľadiska ekotoxicity ako neošetrený materiál a môže byť lepšie aj v porovnaní s niektorými umelými látkami [12]. Medzi pozitívne zmeny tepelne modifikovaného dreva patrí aj jeho zvýšená biologická odolnosť [13-15], rozmerová stabilita [16], tvrdosť povrchu [17, 18], nižšia rovnovážna vlhkosť [19, 20] a tmavšia dekoratívna farba [21-23].

Nevýhodou termicky modifikovaného dreva môže byť zhoršenie niektorých jeho mechanických vlastností, napr. pevnosť v ohybe a v tlaku [24, 25], tvrdosť a pevnosť v šmyku [17], pevnosť v ohybe, modul pružnosti [7, 26], ako aj úbytok na hmotnosti [19, 27].

2 Úbytok na hmotnosti

Úbytok na hmotnosti závisí od druhu dreviny, prostredia, teploty a času pôsobenia.

Kačíková *et al.* [28] termicky upravovali drevo v rozsahu teplôt 113 °C – 271 °C. Zistili, že úbytok na hmotnosti vzrastal s teplotou pôsobenia, napr. pri teplote 158 °C bol 1.53%, a pri teplote 271 °C dosahoval hodnoty 32,97%.

González-Pena *et al.* [29] sledovali zmeny bukového (*Fagus sylvatica*), borovicového (*Pinus sylvestris*) a smrekového (*Picea abies*) dreva pri termickej modifikácii v rozsahu teplôt 190 °C – 245 °C pri rôznych časoch pôsobenia (0,33 h, 1 h, 4 h, 8 h a 16 h). Bukové vzorky mali vyšší úbytok na hmotnosti ako ihličnaté dreviny bez ohľadu na čas pôsobenia; pri bukovom dreve bol úbytok na hmotnosti 0.3% (0,33 h) a 6,7% (16 h) pri 190 °C, a 12,2% (0,33 h) a 27,0% (16 h) pri 245 °C, pri borovicovom dreve 0,6% (0,33 h) a 4,5% (16 h) pri 190 ºC, pri teplote 245 ºC sa pohyboval medzi 5,6% (0,33 h) a 21,5% (16 h). Pri smrekovom dreve bol v rozsahu 1,1% (0,33 h) a 3,6% (16 h) pri 190 ºC a medzi 7,7% (0,33 h) až 26,7% (16 h) pri teplote 245 ºC. Autori dospeli k záveru, že

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and between 7.7% (0.33 h) and 26.7% (16 h) at 245 ºC. These authors concluded that sample weight is more affected by the temperature of the treatment than by the time irrespective of the species under study.

Kučerová *et al.* [30] treated Silver fir wood (*Abies alba*) at the temperature range of 100 °C – 280 °C for 1 hour. They found the mass loss in the range of 7.88% (100 °C) – 52.40% (280 °C).

Mazela *et al.* [31] treated Scots pine (*Pinus sylvestris*) at the temperatures of 160 ºC, 190 ºC, and 220 ºC during 6 h and 24 h in the air and in an atmosphere with water vapour. They found that the mass losses in the presence of air and of water vapour for 6 h were similar, but with 24 h the mass losses in the air were higher, especially for the wood treated at 190 ºC and 220 ºC.

Kim *et al.* [32] found a correlation between the mass loss and the time of the treatment (*P*) of radiata pine (*Pinus radiata*) for several temperatures, with equation (1):

na hmotnosť dreva viac vplýva teplota pôsobenia ako čas pôsobenia a druh dreviny.

Kučerová *et al.* [30] termicky pôsobili na jedľové drevo (*Abies alba*) v teplotnom rozsahu 100 °C – 280 °C počas 1 hodiny. Úbytok na hmotnosti bol 7,88% (100 °C) až 52,40% (280 °C).

Mazela *et al.* [31] upravovali borovicové drevo (*Pinus sylvestris*) pri teplotách 160 ºC, 190 ºC, a 220 ºC počas 6 h a 24 h vo vzduchu aj v atmosfére vodnej pary. Zistili, že v oboch prostrediach boli úbytky na hmotnosti podobné pri čase pôsobenia 6 h, ale pri 24-hodinovom pôsobení bol úbytok vyšší vo vzduchu, najmä pri teplotách úpravy 190 ºC a 220 ºC.

Kim *et al.* [32] zistili koreláciu medzi úbytkom na hmotnosti a časom pôsobenia (*P*) pre borovicové drevo (*Pinus radiata*) pri viacerých teplotách, so závislosťou (1):

$$ML(\%) = A_1 + A_2 ln(P) \quad (1)$$

where *ML* is the percent mass loss (%), *P* is the heating period (hours), and A_1 and A_2 are constants.

kde *ML* je úbytok na hmotnosti (%), *P* je čas pôsobenia (h), a A_1, A_2 sú konštanty.

3 Chemical Changes

The thermal modification influences the chemical composition of wood. It was found that chemical changes are also more influenced by the treatment temperature than the time [25].

At low temperatures between 20 °C – 150 °C, the process of wood drying is occurring, beginning with the loss of free water and finishing with bound water, in the temperature range of 180 °C – 250 °C, the temperature range commonly used for heat treatments, wood undergoes important chemical transformations, and at the temperatures above 250 ºC starts the carbonization processes with the formation of CO_2 and other pyrolysis products [8]. It was found that the pyrolytic decomposition of the wood in the inert atmosphere occurs at mild temperatures for hemicelluloses (250 °C – 300 °C) followed by cellulose (300 °C – 350 °C) and finally lignin (300 °C – 500 °C) [33].

3 Chemické zmeny

Termická modifikácia ovplyvňuje aj chemické zmeny dreva. Tieto zmeny sú tiež viac ovplyvnené teplotou pôsobenia ako jeho trvaním [25].

Pri nízkych teplotách (20 °C – 150 °C) prebieha sušenie dreva, pričom dochádza k odstráneniu najskôr voľnej, neskôr aj viazanej vody, pri teplotách od 180 °C do 250 °C, ktoré sa bežne používajú na termickú modifikáciu, podlieha drevo významným chemickým zmenám, a pri teplotách nad 250 °C začína proces karbonizácie sprevádzaný vznikom CO_2 a iných pyrolýznych produktov [8]. Pyrolytický rozklad dreva začína v inertnej atmosfére pri relatívne nízkych teplotách degradáciou hemicelulóz

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Hemicelluloses are degraded by the organic-acid catalyzed process

Amorphous regions of cellulose are also rapidly decomposed, what leads to the molecular configurations less susceptible to reaction with water [25, 34]. Acid-catalyzed degradation leads to the formation of formaldehyde, furfural, and other aldehydes [16]. Furfural and hydroxymethylfurfural are degradation products of pentoses and hexoses, respectively [35]. At the same time, hemicelluloses undergo dehydration reactions with the decrease of hydroxyl groups [36]. The content of polysaccharides decreases with the severity of the treatment and depends on the wood species [8]. Lignin undergoes depolymerisation in a first, fast stage, and then repolymerises into a more condensed substance [8]. Crystalline cellulose is largely unaffected below 300 °C [25, 34].

(250 °C – 300 °C), neskôr celulózy (300 °C – 350 °C) a nakoniec lignínu (300 °C – 500 °C) [33]. Degradáciu hemicelulóz katalyzujú organické kyseliny.

Amorfné oblasti celulózy sa rozkladajú rýchlo, čo vedie ku konfigurácii, ktorá je menej prístupná reakciám v roztoku [25, 34]. Degradačné reakcie v kyslom prostredí vedú k tvorbe formaldehydu, 2-furaldehydu a ďalších aldehydov [16]. 2-Furaldehyd a 5-hydroxymetyl-2-furaldehyd sú degradačné produkty pentóz, príp. hexóz [35]. Súčasne hemicelulózy podliehajú dehydratačným reakciám, ktoré sú sprevádzané poklesom hydroxylových skupín [36]. Množstvo polysacharidov klesá v závislosti od podmienok pôsobenia a druhu dreviny [8]. V prvej etape termickej úpravy nastáva depolymerzácia lignínu, ktorý potom repolymerizuje za vzniku kondenzovaných štruktúr [8]. Kryštalická celulóza je pomerne odolná pri teplotách do 300 °C [25, 34].

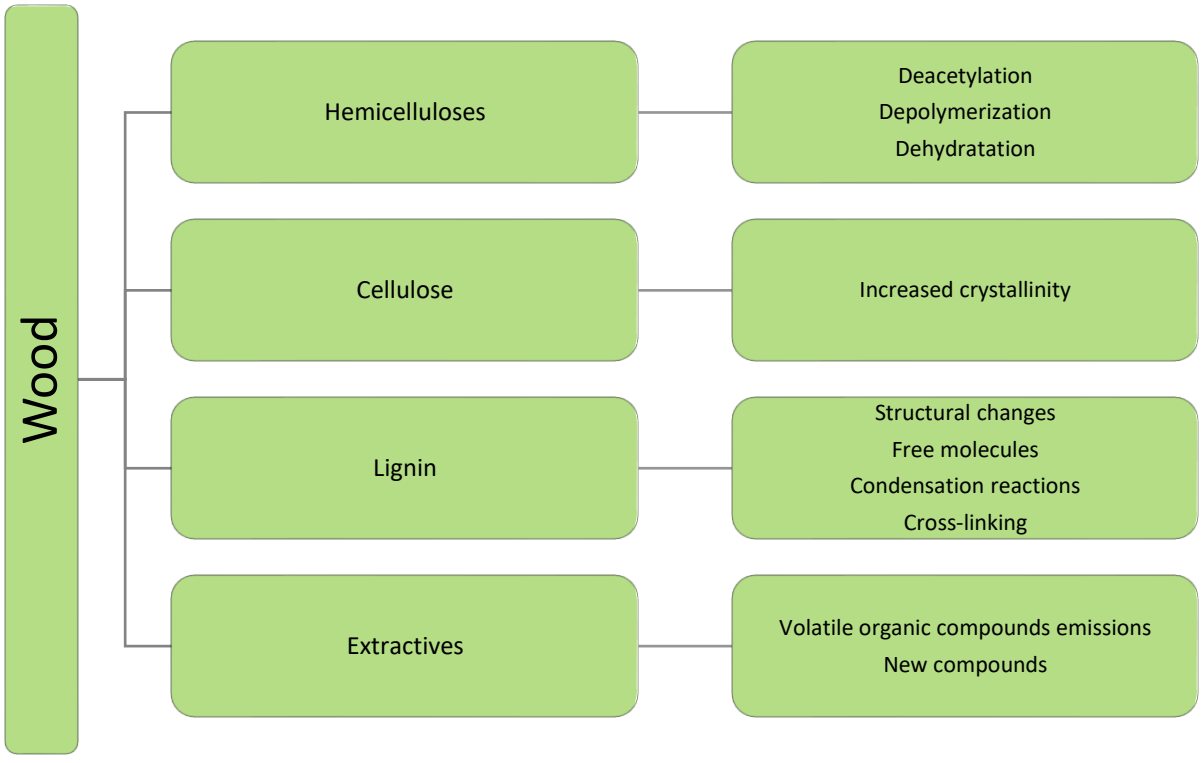

Fig 1. Chemical changes occurring in the main component of wood due to heat treatment (adapted from [8])

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4 Mechanical Properties

One of the main disadvantages of heat-treated wood is the decrease of some mechanical properties, which makes this wood unsuitable for some structural uses. The reduction depends on wood species and process conditions [8]. The modulus of elasticity seems to increase for softer treatments and decrease for more severe treatments [8]. Esteves *et al.* [19] found that in steam heat-treated pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) wood the change in modulus of elasticity was small (maximum decrease of 5% for pine and 15% for eucalypt) but the bending strength was reduced significantly (by 40% at 8% mass loss for pine and 50% at 9% mass loss for eucalypt wood).

Kim *et al.* [32] studied the effect of the thermal treatment at the temperatures of 120 °C, 150 °C, and 180 °C during 4 hours to 96 hours on the bending properties of radiata pine (Pinus radiata) sapwood. Residual MOR of dry samples treated at 120 °C for 12 hours was 98.9%, and at 180 °C for 20 hours it was 72.1%. For green samples treated at 120 °C for 12 hours, residual MOR was 89.2%, and at 180 °C for 20 hours it was 68.5%. Residual MOE decreased less significantly. For dry samples treated at 120 °C for 12 hours it was 93.2%, and at 180 °C for 20 hours it was 91.7%. For green samples treated at 120 °C for 12 hours residual MOE was 94.6%, and at 180 °C for 20 hours it was 86.8%. They also found a correlation between the mechanical properties and the heat treatment conditions, expressed by equations (2) and (3).

4 Mechanické vlastnosti

Jednou z hlavných nevýhod termicky upraveného dreva je pokles niektorých mechanických vlastností, čo ho znevýhodňuje pri jeho použití na konštrukčné účely. Zhoršenie týchto vlastností závisí od druhu dreviny a podmienok úpravy [8]. Modul pružnosti vzrastá pri miernejších podmienkach a klesá pri drastickejšom pôsobení [8]. Esteves *et al.* [19] zistili pri úprave borovicového (*Pinus pinaster*) a eukalyptového (*Eucalyptus globulus*) dreva len malé zmeny modulu pružnosti (maximálny pokles o 5% pre borovicu a 15% pre eukalyptus), ale pevnosť v ohybe bola znížená významne (o 40% pri 8% úbytku na hmotnosti pre borovicu a 50% pri 9% úbytku na hmotnosti pre eukalyptus).

Kim *et al.* [32] skúmali vplyv termickej úpravy pri teplotách 120 °C, 150 °C a 180 °C a trvaní 4 až 96 hodín na ohybové vlastnosti bieľového borovicového dreva (*Pinus radiata*). Výsledné hodnoty MOR suchých vzoriek upravovaných 12 h pri 120 °C klesli oproti pôvodným na 98,9% a na 72,1% pri teplote 180 °C počas 20 hodín. Pri vlhkých vzorkách upravovaných 12 h pri 120 °C bol pokles na 89,2% a na 68,5% pri teplote úpravy 180 °C počas 20 hodín. Pokles hodnôt MOE bol menej výrazný. Výsledné hodnoty MOE suchých vzoriek upravovaných 12 h pri 120 °C klesli oproti pôvodným na 93,2% a na 91,7% pri teplote 180 °C počas 20 hodín. Pri vlhkých vzorkách upravovaných 12 h pri 120 °C bol pokles na 94,6% a na 86,8% pri teplote úpravy 180 °C počas 20 hodín. Bola zistená korelácia medzi mechanickými vlastnosťami a podmienkami termickej úpravy, vyjadrená rovnicami (2) a (3).

$$RPB(\%) = B2 - BO\left(1 - e^{-(B1P)}\right) \quad (2)$$

$$RPB(\%) = A1e^{A2P} \quad (3)$$

where *RPB* is the percent residual bending properties (%), *P* is the heating period (hours), and *A1, A2, B0, B1* and *B2* are the parameters.

The decrease of the mechanical properties of the thermally modified wood was also described by many other authors [26, 28, 30].

kde *RPB* je hodnota výsledná hodnota ohybových vlastností (%), *P* je doba ohrevu (h), a *A1, A2, B0, B1* a *B2* sú parametre.

Pokles pevnostných vlastností termicky modifikovaného dreva bol pozorovaný aj inými autormi [26, 28, 30].

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Boonstra *et al.* [37] studied the reasons for degradation of mechanical properties of thermally modified wood. They stated, that the degradation of hemicelluloses is the major factor for the loss of mechanical strength, affecting especially bending and tensile strength, but also the crystallization of amorphous cellulose might play an important role. Polycondensation reactions of lignin resulting in cross-linking, are proposed as having a positive impact mainly in the longitudinal direction. A close relationship between hemicellulose content and bending strength was also reported by other authors [7, 38].

5 Optical Properties

Colour is the very important property of wood for the final product, and in some cases, it is the determining factor for the selection of a specific wood since the visual decorative point of view is often prevailing [8]. Most researchers use CIELab system to determine the colour changes. The advantage of this system is that it is similar to human vision and very useful for camera or scanner imaging editing.

Kačíková *et al.* [28] studied the effect of the thermal treatment on colour changes in Norway spruce (*Picea abies*) wood. They found that surface colour of samples at the temperature of 221 °C was light brown, then brown to dark brown. At the temperature of 271 °C, the samples were black with a carbonized surface. Chen *et al.* [39] found that the black locust (*Robinia pseudoacacia*) wood flour changed its color characteristics in terms of *L**, *a**, and *b** values when subjected to heat treatment; the initial *L** value for control was 66.9, heat treatment induced a significant decrease in *L** values, measured at 42.8 (in oxygen) and 54.2 (in nitrogen), when the initial moisture content was 0%, the *a** values increased while *b** values decreased after heat treatment. Similar results were observed for Pedunculate oak (*Quercus robur*), Scotch pine (*Pinus sylvestris*), and Silver birch (*Betula verrucosa*) treated at temperatures 160 °C, 180 °C, 210 °C, and 240 °C [40].

Chen *et al.* [39] explained an increase of Δa^* by condensation of proanthocyanidin, lignin and other related extractives under low pH on the heat, and that the byproducts thus formed absorb the complementary light of reddish colour and contribute to the red colour of the wood.

Boonstra *et al.* [37] zisťovali príčiny zhoršovania mechanických vlastností termicky modifikovaného dreva. Uvádzajú, že degradácia hemicelulóz je hlavným faktorom spôsobujúcim stratu mechanických vlastností, najmä pevnosti v ohybe a pevnosti v tlaku, ale takisto kryštalizácia amorfnej celulózy môže zohrávať významnú úlohu. Kondenzačné reakcie lignínu vedúce k jeho zosieťovaniu môžu mať pozitívny vplyv, najmä v pozdĺžnom smere. Významné korelácie medzi množstvom hemicelulóz a pevnosťou v ohybe zistili aj iní autori [7, 38].

5 Optické vlastnosti

Farba je veľmi dôležitá vlastnosť dreva v jeho finálnych produktoch a v niektorých prípadoch môže byť rozhodujúcim faktorom pre výber dreviny, keďže vizuálne hľadisko je často rozhodujúce z estetického hľadiska [8]. Väčšina výskumníkov používa CIELab systém na sledovanie farebných zmien. Výhodou tohto systému je jeho podobnosť s ľudským videním a je tiež vhodné na spracovanie kamerou alebo skenerom.

Kačíková *et al.* [28] študovali vplyv termickej úpravy na farebné zmeny smrekového dreva (*Picea abies*). Zistili, že pri zvyšujúcej sa teplote do 221 °C sa farba menila od slabo hnedej až po tmavohnedú. Pri teplote 271 °C boli vzorky čierne so zuhoľnateným povrchom. Chen *et al.* [39] skúmali farebné zmeny termicky upraveného agátového dreva (*Robinia pseudoacacia*) hodnotami *L**, *a**, and *b**. Počiatočná hodnota *L** bola 66,9, termická úprava spôsobila jej významný pokles na 42,8 (v kyslíku) a na 54,2 (v dusíku) pri nulovej počiatočnej vlhkosti. Hodnota *a** vzrastala a hodnota *b** klesala vplyvom zvýšenej teploty. Podobné zmeny boli pozorované pri dubovom (*Quercus robur*), borovicovom (*Pinus sylvestris*) a brezovom (*Betula verrucosa*) dreve, ktoré boli upravované pri teplotách 160 °C, 180 °C, 210 °C a 240 °C [40].

Chen *et al.* [39] vysvetľujú vzrast Δa^* kondenzáciou proantokyanidínu, lignínu a niektorých extraktívnych látok vplyvom tepla pri nízkych hodnotách pH, pričom vznikajúce vedľajšie produkty absorbujú doplnkové žiarenie červenej frby a tým prispievajú k červenému zafarbeniu dreva. V prítomnosti vody kombinácia

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In the presence of water, combining high temperature and oxygen atmosphere, heating generally induces hydrolysis reactions in wood, which could result in the formation of lower molecular weight yellow phenolic substances, such as flavonoids, which results in a decrease of *Δb**. Their results suggested that oxygen as an oxidation medium plays a vital role in the darkening of wood during heat treatment. The decrease in lightness (*L**) indicates that many components absorbing visible light are formed during heat treatment.

In general, colour could be used for predicting the properties of heat-treated wood. Todorovic *et al.* [41] observed that the majority of examined properties had a linear correlation with ΔL* and ΔE*, while ΔE* was a better predictor for all properties, except for density of heartwood. Candelier *et al.* [11] reviewed the prediction of the durability of heat treated wood by colour measurement.

9 Surface Quality

The thermal modification also improves the surface quality of wood. This property is important in relation to wood flammability [8]. Priadi and Hiziroglu [42] treated Ceylon cedar (*Melia azedarch*), mahogany (*Swietenia macrophyla*), red oak (*Quercus falcate*), and Southern pine (*Pinus taeda*) wood at 130 °C and 200 °C for 2 h and 8 h. They observed that the oak showed the roughest surface with an average R_a value of 12.3 μm. Exposing the samples to the temperature of 130 °C for 2 h resulted in only 4.4% improvement in their R_a values. All specimens kept in the oven at 130 °C for 8 h had smoother surface quality. Average roughness values of the samples exposed to the temperature of 200 °C for 8 h had values lower about 17.8% than those of control samples. Eastern red cedar samples exposed to 190 °C for 8 h showed 85% lower values for above corresponding comparison.

Bakar *et al.* [17] reported that the surface quality of red oak (*Quercus rubra*), Eastern red cedar (*Juniperus virginiana*), and rubberwood (*Hevea brasiliensis*) treated at the temperatures of 120 °C and 190 °C for 2 h and 8 h improved with the increasing temperature and the exposure time. Among the average of surface roughness measurements for three species, red oak had the roughest surface quality, followed by

vysokej teploty a oxidačnej atmosféry spôsobuje hydrolýzne reakcie v dreve, čo môže viesť k vzniku nízkomolekulových fenolických látok, napr. flavonoidov a výsledkom je pokles *Δb**.

Tieto výsledky naznačujú, že kyslík ako oxidačné médium hrá dôležitú úlohu pri tmavnutí dreva počas jeho tepelnej úpravy. Pokles svetlosti (*L**) poukazuje na vznik mnohých zlúčenín absorbujúcich viditeľné žiarenie počas termickej modifikácie dreva.

Zmeny farby môžu byť použité pre odhad vlastností termicky upraveného dreva. Todorovic *et al.* [41] zistili, že sledované vlastnosti majú lineárnu koreláciu s *ΔL** a *ΔE**, pričom *ΔE** vykazovalo lepšiu koreláciu so všetkými vlastnosťami, okrem hustoty jadrového dreva. Candelier *et al.* [11] skúmali závislosť medzi trvanlivosťou termicky upraveného dreva a zmenami farby.

9 Kvalita povrchu

Termická modifikácia takisto zlepšuje kvalitu povrchu dreva. Táto vlastnosť je dôležitá aj pri odolnosti voči jeho horľavosti [8]. Priadi a Hiziroglu [42] upravovali cédrové (*Melia azedarch*), mahagónové (*Swietenia macrophyla*), dubové (*Quercus falcate*) a borovicové (*Pinus taeda*) drevo pri teplotách 130 °C a 200 °C počas 2 a 8 hodín. Zistili, že dubové drevo malo najdrsnejší povrch s hodnotou R_a 12,3 μm. Úprava pri teplote 130 °C počas 2 h ho zlepšila len 4,4%. Všetky vzorky upravené pri teplote 130 °C počas 8 h mali hladší povrch. Priemerné hodnoty vzoriek upravených pri teplote 200 °C počas 8 h mali nižšie hodnoty o 17,8 % ako kontrolné vzorky. Cédrové drevo upravené pri teplote 190 °C počas 8 h malo o 85 % nižšie hodnoty v porovnaní s predchádzajúcimi.

Bakar *et al.* [17] uvádzajú, že kvalita povrchu dubového (*Quercus rubra*), cédrového (*Juniperus virginiana*) a kaučukového (*Hevea brasiliensis*) dreva upravovaného pri teplotách 120 °C a 190 °C počas 2 a 8 h sa zlepšovala so vzrastajúcou teplotou a dlhším trvaním úpravy. Dubové drevo malo najdrsnejší povrch (9,93 μm), hladší povrch mal kaučukovník (4,57 μm) a najhladší cédrové (2,60 μm).

Podľa Bakara *et al.* [17] zlepšenie kvality povrchu dreva upravovaného pri vyšších teplotách a dlhších časoch pôsobenia môže mať súvislosť so zmenami v biochemickom zložení bunkových stien.

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rubber wood and Eastern red cedar with average values of 9.93 μm, 4.57 μm and 2.60 μm, respectively.

Bakar *et al.* [17] stated, that the enhanced surface quality of the wood exposed to a higher temperature for a longer period of time could possibly be related to the changes of biochemical constituents in the cell wall.

10 Fire-technical Characteristics

Research on the influence of the thermal modification on fire-technical characteristics is scarce.

According to the Termowood Handbook [43] the rate of the heat release level (RHR) of the heat-treated pine was about 10 kW greater than that of the untreated pine, in the total heat rate (THR), an increase of about 15% due to the heat treatment was observed, smoke production was roughly doubled, and the ignition time was shortened by 30%. However, they stated that ThermoWood does not differ significantly from normal wood when it comes to fire safety and that ThermoWood is in fire class D.

Čekovská *et al.* [44] studied the behaviour of the spruce wood treated at the temperatures of 160 °C, 180 °C, and 210 °C after the exposure to the direct flame. They found, that the open-flame burning caused a lower mass loss in the thermally modified spruce wood than in the untreated wood. After the direct flame was removed from the wood 10 min to 15 min into the test, there was no after-flame, and the mass loss was minimal, up to 0.54%.

Čekovská *et al.* [45] found that the same treatment of teak wood (*Tectona grandis*) caused the greater mass loss in open flame burning than in the untreated wood. Also, they found that thermally treated teak wood at all temperatures has higher burn rates than untreated wood.

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10 Požiarno-technické vlastnosti

Vplyv termickej modifikácie na požiarno-technické vlastnosti dreva je v súčasnosti stále nedostatočne preskúmaný.

Podľa Thermowood Handbook [43] úroveň rýchlosti uvoľňovania tepla (RHR) tepelne upraveného borovicového dreva bola asi o 10 kW väčšia ako pri pôvodnom dreve, celkové uvoľnené teplo (THR) vzrástlo asi o 15%, tvorba dymu bola približne dvojnásobná a čas vznietenia sa skrátil asi o 30%. Autori uvádzajú, že ThermoWood sa významne nelíši od bežného dreva, pokiaľ ide o požiarnu bezpečnosť a že ThermoWood je v požiarnej triede D.

Čekovská *et al.* [43] skúmali zmeny smrekového dreva upraveného pri teplotách 160 °C, 180 °C a 210 °C po jeho vystavení priamemu plameňu. Zistili, že pôsobenie otvoreného plameňa spôsobilo menší úbytok na hmotnosti v termicky upravenom dreve ako v pôvodnom. Po odstránení priameho plameňa z dreva 10 min až 15 minút testu nedošlo k žiadnemu spätnému vzplanutiu a straty na hmotnosti boli minimálne , menej ako 0,54%.

Čekovská *et al.* [44] pri rovnako upravenom tíkovom (*Tectona grandis*) zistili väčší úbytok na hmotnosti pri pôsobení priameho plameňa ako v prípade neupraveného dreva. Tíkové drevo modifikované pri všetkých teplotách malo vyššiu rýchlosť horenia v porovnaní s neupraveným drevom.

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References / Literatúra

[1] Evans PD, Michell AJ, Schmalzl KJ. 1992. Studies of the degradation and protection of wood surfaces. Wood Science and Technology 26(2):151-63. DOI: https://doi.org/10.1007/BF00194471

[2] Hon DNS. 1994. Degradative effects of ultraviolet-light and acid-rain on wood surface quality. Wood and Fiber Science 26(2):185-91.

[3] Teaca C-A, Rosu D, Bodirilau R, Rosu L. 2013. Structural Changes in Wood under Artificial UV Light Irradiation Determined by FTIR Spectroscopy and Color Measurements - A Brief Review. Bioresources 8(1):1478-507. DOI: https://doi.org/10.15376/biores.8.1.1478-1507

[4] Huang H-L, Lin C-C, Hsu K. 2015. Comparison of resistance improvement to fungal growth on green and conventional building materials by nano-metal impregnation. Building and Environment 93:119-27. DOI: https://doi.org/10.1016/j.buildenv.2015.06.016

[5] Ahmed B, French JRJ, Vinden P. 2000. Boron protection of simulated wooden houses against *Coptotermes acinaciformis* (Froggatt) (*Isoptera:Rhinotermitidae*) in an accelerated field simulator. Material Und Organismen 33(4):289-318.

[6] Yang D-Q, Wan H, Wang X-M, Liu Z-M. 2007. Use of fungal metabolites to protect wood-based panels against mould infection. Biocontrol 52(3):427-36. DOI: https://doi.org/10.1007/s10526-006-9022-8

[7] Esteves BM, Domingos IJ, Pereira HM. 2008. Pine wood modification by heat treatment in air. Bioresources 3(1):142-54.

[8] Esteves BM, Pereira HM. 2009. Wood modification by heat treatment: A review. Bioresources 4(1):370-404.

[9] Palanti S, Feci E, Torniai AM. 2011. Comparison based on field tests of three low-environmental-impact wood treatments. International Biodeterioration & Biodegradation 65(3):547-52. DOI: https://doi.org/10.1016/j.ibiod.2010.12.012

[10] Pétrissans M, Pétrissans A, Gérardin P. 2007. Check the durability of heat-treated beech wood. Tracés, Bulletin technique Technologie du bois de la Suisse Romande 17:12-6.

[11] Candelier K, Thevenon M-F, Petrissans A, Dumarcay S, Gerardin P, Petrissans M. 2016. Control of wood thermal treatment and its effects on decay resistance: a review. Annals of Forest Science 13. DOI: https://doi.org/10.1007/s13595-016-0541-x

[12] Van Eetvelde G, De Geyter P, Marchal P, Stevens M. 1998. Aquatic toxicity research of structural materials. *29th Annual meeting, international research group on wood Protection.*

[13] Calonego FW, Durgante Severo ET, Furtado EL. 2010. Decay resistance of thermally-modified *Eucalyptus grandis* wood at 140 °C, 160 °C, 180 °C, 200 °C and 220 °C. Bioresource Technology;101(23):9391-4. DOI: https://doi.org/10.1016/j.biortech.2010.06.119

[14] Hakkou M, Petrissans M, Gerardin P, Zoulalian A. 2006. Investigations of the reasons for fungal durability of heat-treated beech wood. Polymer Degradation and Stability 91(2):393-7. DOI: https://doi.org/10.1016/j.polymdegradstab.2005.04.042

[15] Shi JL, Kocaefe D, Amburgey T, Zhang J. 2007. A comparative study on brown-rot fungus decay and subterranean termite resistance of thermally-modified and ACQ-C-treated wood. Holz Als Roh-Und Werkstoff 65(5):353-8. DOI: https://doi.org/10.1007/s00107-007-0178-4

[16] Tjeerdsma BF, Boonstra M, Pizzi A, Tekely P, Militz H. 1998. Characterisation of thermally modified wood: molecular reasons for wood performance improvement. Holz Als Roh-Und Werkstoff 56(3):149-53. DOI: https://doi.org/10.1007/s001070050287

[17] Bakar BFA, Hiziroglu S, Tahir PM. 2013. Properties of some thermally modified wood species. Materials & Design 43:348-55. DOI: https://doi.org/10.1016/j.matdes.2012.06.054

[18] Gunduz G, Korkut S, Aydemir D, Bekar I. 2009. The density, compression strength and surface hardness of heat treated Hornbeam (*Carpinus betulus*) wood. Maderas-Ciencia Y Tecnologia 11(1):61-70. DOI: https://doi.org/10.4067/S0718-221X2009000100005

[19] Esteves B, Marques AV, Domingos I, Pereira H. 2007. Influence of steam heating on the properties of pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) wood. Wood Science and Technology 41(3):193-207. DOI: https://doi.org/10.1007/s00226-006-0099-0

[20] Gunduz G, Niemz P, Aydemir D. 2008. Changes in specific gravity and equilibrium moisture content in heat-treated fir (*Abies nordmanniana subsp bornmulleriana* Mattf.) wood. Drying Technology 26(9):1135-9. DOI: https://doi.org/10.1080/07373930802266207

[21] Bekhta P, Niemz P. 2003. Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood. Holzforschung 57(5):539-46. DOI: https://doi.org/10.1515/HF.2003.080

[22] Brischke C, Welzbacher CR, Brandt K, Rapp AO. 2007. Quality control of thermally modified timber: Interrelationship between heat treatment intensities and CIE L*a*b* color data on homogenized wood samples. Holzforschung 61(1):19-22. DOI: https://doi.org/10.1515/HF.2007.004

[23] Gonzalez-Pena MM, Hale MDC. 2009. Colour in thermally modified wood of beech, Norway spruce and Scots pine. Part 1: Colour evolution and colour changes. Holzforschung 63(4):385-93. DOI: https://doi.org/10.1515/HF.2009.078

[24] Unsal O, Ayrilmis N. 2005. Variations in compression strength and surface roughness of heat-treated Turkish river red gum (*Eucalyptus camaldulensis*) wood. Journal of Wood Science 51(4):405-9. DOI: https://doi.org/10.1007/s10086-004-0655-x

[25] Yildiz S, Gezer ED, Yildiz UC. 2006. Mechanical and chemical behavior of spruce wood modified by heat. Building and Environment 41(12):1762-6. DOI: https://doi.org/10.1016/j.buildenv.2005.07.017

[26] Shi JL, Kocaefe D, Zhang J. 2007. Mechanical behaviour of Quebec wood species heat-treated using ThermoWood process. Holz Als Roh-Und Werkstoff 65(4):255-9. DOI: https://doi.org/10.1007/s00107-007-0173-9

[27] Alen R, Kotilainen R, Zaman A. 2002. Thermochemical behavior of Norway spruce (*Picea abies*) at 180-225 °C. Wood Science and Technology 36(2):163-71. DOI: https://doi.org/10.1007/s00226-001-0133-1

[28] Kacikova D, Kacik F, Cabalova I, Durkovic J. 2013. Effects of thermal treatment on chemical, mechanical and colour traits in Norway spruce wood. Bioresource Technology 144:669-74. DOI: https://doi.org/10.1016/j.biortech.2013.06.110

[29] Gonzalez-Pena MM, Curling SF, Hale MDC. 2009. On the effect of heat on the chemical composition and dimensions of thermally-modified wood. Polymer Degradation and Stability 94(12):2184-93. DOI: https://doi.org/10.1016/j.polymdegradstab.2009.09.003

[30] Kučerová V, Lagaňa R, Výbohová E, Hýrošová T. 2016. The effect of chemical changes during heat treatment on the color and mechanical properties of fir wood. Bioresources 11(4):9079-94. DOI: https://doi.org/10.15376/biores.11.4.9079-9094

[31] Mazela B, Zakrzewski R, Grzeskowiak W, Cofta G, Bartkowiak M. 2003. Preliminary research on the biological resistance of thermally modified wood. *First European Conference on Wood Modification.* 113-9.

[32] Kim GH, Yun KE, Kim JJ. 1998. Effect of heat treatment on the decay resistance and the bending properties of radiata pine sapwood. Material Und Organismen 32(2):101-8.

[33] Carrier M, Loppinet-Serani A, Denux D, Lasnier J-M, Ham-Pichavant F, Cansell F, *et al.* 2011. Thermogravimetric analysis as a new method to determine the lignocellulosic composition of biomass. Biomass & Bioenergy 35(1):298-307. DOI: https://doi.org/10.1016/j.biombioe.2010.08.067

[34] Yildiz S, Gumuskaya E. 2007. The effects of thermal modification on crystalline structure of cellulose in soft and hardwood. Building and Environment 42(1):62-7. DOI: https://doi.org/10.1016/j.buildenv.2005.07.009

[35] Nuopponen M, Vuorinen T, Jamsa S, Viitaniemi P. 2004. Thermal modifications in softwood studied by FT-IR and UV resonance Raman spectroscopies. Journal of Wood Chemistry and Technology 24(1):13-26. DOI: https://doi.org/10.1081/WCT-120035941

[36] Weiland JJ, Guyonnet R. 2003. Study of chemical modifications and fungi degradation of thermally modified wood using DRIFT spectroscopy. Holz Als Roh-Und Werkstoff 61(3):216-20. DOI: https://doi.org/10.1007/s00107-003-0364-y

[37] Boonstra MJ, Van Acker J, Tjeerdsma BF, Kegel EV. 2007. Strength properties of thermally modified softwoods and its relation to polymeric structural wood constituents. Annals of Forest Science 64(7):679-90. DOI: https://doi.org/10.1051/forest:2007048

[38] Winandy JE, Lebow PK. 2001. Modeling strength loss in wood by chemical composition. Part I. An individual component model for southern pine. Wood and Fiber Science 33(2):239-54.

[39] Chen Y, Fan YM, Gao JM, Stark NM. 2012. The effect of heat treatment on the chemical and color change of black locust (*Robinia pseudoacacia*) wood flour. Bioresources 7(1):1157-70.

[40] Barcik S, Gasparik M, Razumov EY. 2015. Effect of temperature on the color changes of wood during thermal modification. Cellulose Chemistry and Technology 49(9-10):789-98.

[41] Todorovic N, Popovic Z, Milic G, Popadic R. 2012. Estimation of heat-treated beechwood properties by color change. Bioresources 7(1):799-815.

[42] Priadi T, Hiziroglu S. 2013. Characterization of heat treated wood species. Materials & Design 49:575-82. DOI: https://doi.org/10.1016/j.matdes.2012.12.067

[43] ThermoWood Handbook. 2003. Finnish Thermowood Association; Helsinki, Finland.

[44] Cekovska H, Gaff M, Osvald A, Kacik F, Kubs J, Kaplan L. 2017. Fire Resistance of Thermally Modified Spruce Wood. Bioresources 12(1):947-59.

[45] Cekovska H, Gaff M, Osvaldova LM, Kacik F, Kaplan L, Kubs J. 2017. *Tectona grandis* Linn. and its Fire Characteristics Affected by the Thermal Modification of Wood. Bioresources 12(2):2805-17. DOI: https://doi.org/10.15376/biores.12.2.2805-2817