

THE INFLUENCE OF THERMAL MODIFICATION ON THE RESISTANCE TO WATER IMPACT PROPERTIES AND STRENGTH OF WOOD USED IN OUTDOOR CONDITIONS

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ABSTRACT

In this study the influence of thermal modification on the resistance of wood to the impact of water and mechanical properties and to compare the durability of thermally modified and coated wood products operating in wet conditions was investigated. It was found that the weight of thermally unmodified non-coated oak wood after 48 h of soaking increased on average up to ~ 15%, and the weight of coated oak wood increased up to ~ 8%. If wood was thermally modified, the weight of non-coated oak wood increased up to ~ 9%, and the weight of coated oak wood increased up to ~ 5%. After 168 h of soaking these change is about 2 times larger. In the case of pine wood compared to oak wood these change of weight after 48 h is about 2.0 – 2.4 times and after 168 h about 1.4 - 2.0 larger. It can be stated that wooden constructions intended to be used in very wet conditions should be made of thermally modified wood without coating. Thermally modified wood will have greater dimensional and shape stability. Thermal modification reduces the swell up to 1.6 times in the case of oak, more than 2 times in the case of pine.

KEYWORDS: Coating, sorption properties, strength, thermal modification, wood.

INTRODUCTION

The problem of the durability of the wood becomes relevant as the wood is exposed to the atmosphere impacts, rains on it, and therefore has the ability to absorb large amounts of water. This causes wood deformation, swelling, and, after longer exposure of these factors, wood is vulnerable to destructive fungus and biological pests. In construction, the durability of wood in the open atmosphere is usually enhanced by the chemical treatment of the wood or by coating

with various coatings. The effect of moisture can be reduced by coating wood with various paints, waxes, oils, biocides or a combination of thereof (Wood Handbook 2010, Zlahtic-Zupanc et al. 2018). However, this way of treating wood in the paths is undesirable in valuable natural areas, as chemicals washed out of wood can damage the environment and coating is not compatible with the natural environment. Therefore, there is a search for alternative ways of increasing the durability of outdoor wood that would be suitable for use in natural environment conditions.

One of the most effective modifications to increase the resistance and durability of wood is thermal modification. It has been found that thermal modification improves the resistance of the wood to the atmospheric impact, the surface of the thermally modified wood, which is naturally worn due to the environmental impact, is better than that of the thermally unmodified (Deka et al. 2007). Although not moderately, thermally modified at 170–230°C, wood swelling factors due to structural changes are significantly reduced (Esteves et al. 2008, Cao et al. 2011). This is relevant to wooden structures operating under extremely wet and changing conditions.

It is known that the biological durability of thermally modified wood is superior to unmodified wood. The main factor is the thermochemical modification of cell wall polymers (predominantly hemicellulose) (Sustersic et al. 2010, Candelier et al. 2013, Mohareb et al. 2011). The resistance to biological effects correlates well with weight loss and chemical composition of wood after thermal modification. Therefore, knowing how much wood has lost its weight or its chemical composition or its biological durability can be predicted. Thermal modification of the wood first causes the breakdown of hemicellulose and the removal of many extractive substances. It is known that the hydroxyl groups, which are in hemicellulose, are the main determinants of the process of wood shrinkage - swelling. In addition, hemicellulose is one of the main 'nutrients' for biological pests that destroy wood. Some of wood mechanical properties, which in many cases deteriorate are changing in a positive direction due to thermal modification of the wood. In many cases, after heat treatment chemical changes influenced structure of the cell walls, density of wood and e.g. content of resin in conifer wood, etc.

However, thermal modification changes the mechanical properties of wood, which often deteriorate (Jimenez et al. 2011, Borrega and Karenlampi 2007, Kol et al. 2015). The reduction in the resistance of thermally modified wood to static bending and tension perpendicular to the grain correlates with the level of hemicellulose depolymerisation reactions, which mostly depend on the temperature of the process (Borrega and Karenlampi 2007, Hannouz et al. 2015, Younsi et al. 2010). Mechanical strength is not the most important feature of thermally modified wood and therefore there is no change in the mechanical properties of wood after thermal analysis. There is also a lack of research on thermally modified wood behaviours under very humid conditions.

The aim of the work is to evaluate the influence of thermal modification on the resistance of wood to the impact of water and mechanical properties and to compare the durability of thermally modified and coated wood products operating in wet conditions.

MATERIALS AND METHODS

Oak and pine wood samples with dimensions of 100 × 100 × 15 mm and density of 515 - 655 kg·m⁻³ and 435 - 470 kg·m⁻³ were used for research according to standard EN 323. Humidity varied between 8.5% and 10.2% (determined by a humidity meter according to standard EN 13183-2). Wood fibre direction was random; semi-tangential, semi-radial incision prevailed.

A summary of the research is presented in Fig. 1. Before the test, all samples were conditioned for 14 days in a room with a temperature of $20 \pm 2^\circ\text{C}$, relative humidity within the range was of 60-62% (standard EN 408, point 8). After conditioning, the parts of the oak and pine wood samples were left in the conditioned room and the rest were dried to a constant weight at 103°C . In order to avoid drying defects during thermal modification according to standard EN 13183-1 and heated at temperatures of 140°C , 165°C , 190°C and 215°C for 3 hours. After thermal modification, the samples were cooled in a conditioned room.

The temperature and duration of the thermal modification has been selected after analysing other works and changes in the wood due to temperature effects (Younsi et al. 2010, Kol 2010, Albrektas and Navickas 2017). Samples for heating were selected randomly.

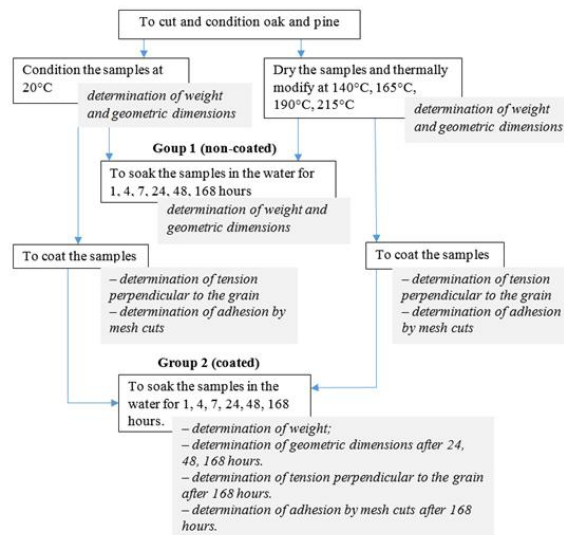


Fig. 1: A summary of the experimental plan.

Thermally modified and unmodified samples were divided into 2 groups. Samples in group 1 were not coated with paints. The surface of group 2 samples was grounded manually, the graininess of used abrasive material is P120 according to FEPA (Federation of European Producers of Abrasives), then the samples were coated on all sides with 2-layer brush with commercial paints intended for various surfaces for outdoor coating, water-based paints, where non-volatile materials are 62.6% (ISO 3251, 2008), density is $1.451 \text{ g}\cdot\text{cm}^{-3}$ (ISO 2811-1, 2016). Samples were coated according to the manufacturer's recommendations. The second layer was coated, when the first one completely dried, after one day. The coated samples were dried in a conditioned room for 7 days. Subgroup codes and sample processing methods are presented in Tab. 1.

Tab. 1: Marking of samples.

Thermal modification temperature (°C)	Subgroup name (oak wood)		Subgroup name (pine wood)	
	Group 1 Non-coated	Group 2 Coated	Group 1 Non-coated	Group 2 Coated
20 (unmodified)	O.I.20	O.II.20	P.I.20	P.II.20
140	O.I.140	O.II.140	P.I.140	P.II.140
165	O.I.165	O.II.165	P.I.165	P.II.165
190	O.I.190	O.II.190	P.I.190	P.II.190
215	O.I.215	O.II.215	P.I.215	P.II.215

Samples of O.I.20, O.II.20, P.I.20 and P.II.20 subgroups are samples that were in air-conditioned state. Five samples of each subgroup were randomly selected and their geometric parameters (accuracy of 0.02 mm), weight (accuracy of 0.01 g) were determined. Thermally modified and unmodified samples of Group 1 and Group 2 were soaked in distilled water. During the entire soaking period, the samples were completely immersed in water at a temperature of $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ under atmospheric pressure.

After 1, 4, 7, 24, 48 and 168 hours, the weight of samples was fixated. After 24, 48 and 168 hours, the dimensions of the samples were recorded. The relative change in weight and dimensions across and along the grain was calculated.

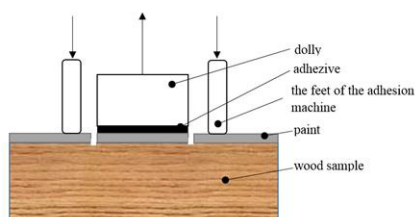


Fig. 2: Test of tension perpendicular of the samples to the grain.

Tension perpendicular of the sample to the grain and adhesion by the mesh cut method was determined before the soaking process and after 168 hours (7 days) of soaking. According to ISO 4624 (2016), tension perpendicular of the sample to the grain was determined in each sample by tearing 4 zones, using dollies of 2 cm diameter (Fig. 2). A visual inspection of the tearing site was performed to determine the mechanism of failure.

Determination of adhesion by mesh cuts was done according to standard ISO 2409 (2013). Cut direction is 45° to grain. The distance between the cuts is 3 mm taking into account that the thickness of the coating is $> 120 \mu\text{m}$ (thickness is measured according to EN ISO 2808 (2019), method 4A). Peeled off coating particles were removed using a pressure sensitive adhesive tape. The test was carried out according to the requirements of the standard EN ISO 13076 (2012), with an average illumination of 900 lx. The coefficient of variation of the test results did not exceed 8%.

RESULTS AND DISCUSSION

Influence of thermal modification and coating on the sorption properties of wood

The modified, unmodified and coated specimens were soaked in water. The relative change in weight of coated and non-coated oak and pine wood samples, when soaking in water, is shown in Fig. 3.

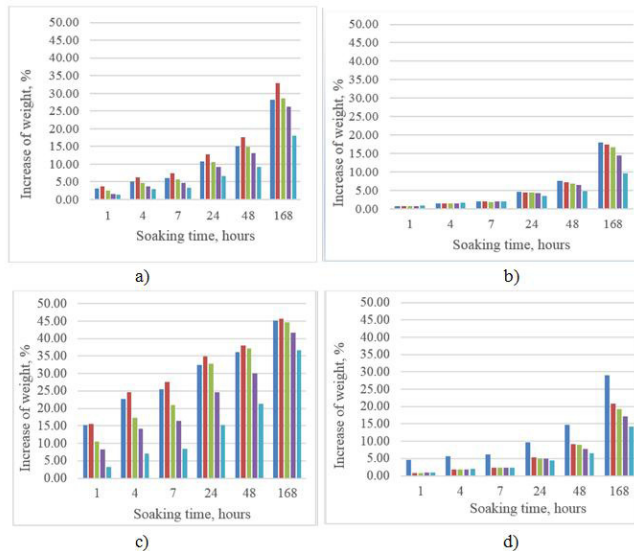


Fig. 3: The increase of oak wood O.I (a) and O.II (b) and pine wood P.I (c) and P.II (d) samples weight (%), when soaking them in the water, when the samples are thermally unmodified at 20°C and thermally modified at temperatures (°C):

■ 20 ■ 140 ■ 165 ■ 190 ■ 215

It can be seen, in the case of oak wood (Fig. 3a,b), the weight of thermally unmodified non-coated wood after 48 h of soaking increased on average up to ~ 15%, and the weight of coated wood increased up to ~ 8%. If wood was thermally modified at ~ 215°C, the weight of non-coated wood increased up to ~ 9%, and the weight of coated wood increased up to ~ 5%. The difference (of thermally unmodified and thermally modified) was about 1.7 and 1.6 times, respectively.

After 168 h of soaking, the weight of thermally unmodified non-coated wood increased up to 28%, and the weight of coated wood rose up to 18%. If wood was thermally modified at 215°C, its weight (non-coated and coated) increased approximately to 18 and 10% respectively. The difference between thermally unmodified and thermally modified oak wood is about 1.6 and 1.8 times.

In the case of pine wood (Fig. 3c,d), more significant changes in results are seen after 48 hours of soaking. The weight of thermally unmodified non-coated wood has increased up to ~ 36%, the weight of thermally unmodified coated pine increased approximately to ~ 15%. If wood was thermally modified at 215°C, the weight of non-coated and coated pine increased up to 21 and 7% respectively. The difference between thermally unmodified and thermally modified wood samples was 1.7 and 2.1 times.

After 168 h of soaking, the weight of thermally unmodified non-coated wood increased up to ~ 45% and coated wood samples up to ~ 29%. If wood was thermally modified at 215°C, the weight of non-coated and coated pine increased up to 37 and 14% respectively. In this case, the

difference between thermally unmodified and thermally modified wood samples (non-coated and coated) was 1.2 and 2.1 times. The results of these tests could be explained by differences in the structure of pine and oak wood.

In the case of non-coated wood, thermally modified samples at 140°C can be excluded. They soaked more water than thermally non-coated thermally unmodified and modified wood samples at higher temperatures (Fig. 3a,c). The wood, after heating at 140°C, is very dry (to get completely dry wood, it can be dried and at 103°C, as indicated in the standard EN 13183-1). However, when heating at this temperature, there are no significant changes in the structure of wood or chemical composition, determining its hygroscopicity (Sundqvist 2004, Yildiz et al. 2006, Garrote et al. 1999). Thus, it can be stated that at this temperature the wood is dried rather than modified (almost no increase in hydrophobicity). Unmodified wood had a higher moisture content (about 10.3 - 11.2%) before soaking. This resulted in a greater increase in the weight of the soaked dry wood, i.e. it absorbed more water at the same time. The coating has significantly slowed down the sorption process of samples, when taking into account thermally modifying the samples at all temperatures.

Swelling along and across the grain

In the case of both oak and pine, irrespective of the coating and thermally modifying temperature, the swelling along the grain was up to 1%. The variation in the dimensions of the oak and pine samples transversely soaking “across” in water is shown in Fig. 4.

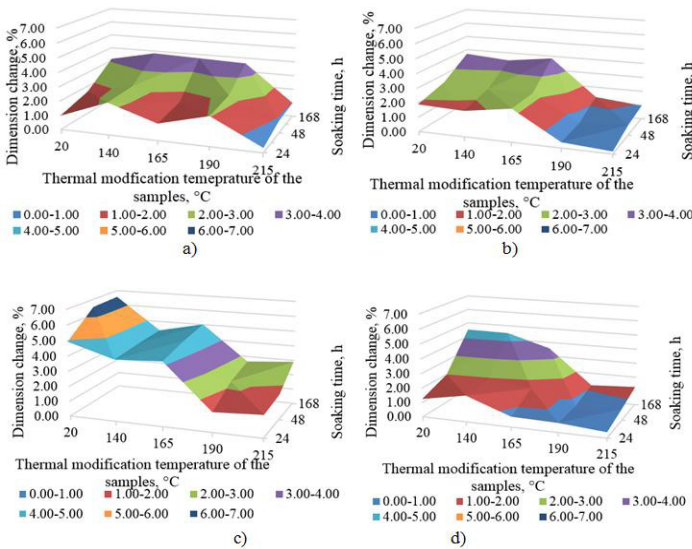


Fig. 4: The change in dimensions of oak wood O.I (a) and O.II (b) and pine wood P.I (c) and P.II (d) samples across the grain, after soaking in water.

After 48 hours of soaking oak wood, as the thermally modifying temperature increases, the swelling decreases from approximately ~ 1.6% (when the wood was thermally unmodified) to 1% (thermally modified samples at 215°C). In the case of pine wood, slightly higher results were obtained: from ~ 6.5% for non-heated pine wood to 7% for heated wood at 215°C.

When increasing heating temperature from ambient temperature to 215°C, in the case of oak wood, the average swell during 168 hours was approximately ~ 1%. In this case, the coated and non-coated samples have similar values.

In the case of pine wood, the average swell during 168 hours of non-coated samples ranged from 6.6% (for thermally unmodified wood) to 2.9% (for thermally modified wood). In the case of coated pine samples, the same range was from 4.5 to 1.3%.

It was identified that the weight, of the samples during the soaking increased more than dimensions. The biggest change in the weight of oak was 32% and pine 45%, respectively. In this case, the dimensions of the oak across the grain increased up to 4%, the pine up to 6.5%. The change in the mass of the wood is related to the change in both free and bound moisture. It is known that the dimension of wood across the fibre can usually vary within a few percent (Esteban et al. 2005). It is only related to the change in the bound moisture, which is usually found in the cell walls (microcapillaries) of wood. Drying-swelling processes usually occur in wood, with humidity ranging from 0 to 30%. The change in the mass of the wood is related to the change in both free and bound moisture. The maximum moisture content of the wood depends on the density of the wood (higher density wood may contain less free moisture due to the smaller volume of macrocapillary where the free moisture builds up) and can reach 100% and more (Hrčka 2017, Shi et al. 2000). This can be explained by the greater change in the mass of pine trees compared to oak wood.

Tension perpendicular of the wood to the grain.

Generally, if oak wood was thermally modified from ambient temperature to 215°C, the force required to tear the wood across the grain reduces about 2.5 times, in the case of pine wood up to 10 times. As mentioned, the cut of the coated samples varied (mixed, tangential, and radial). In the case of thermally unmodified samples, tearing off the coating, the degradation of "wood - coating" composite varied. It decomposes both in the "wood-coating" area and the wood. Such degradation is most likely associated with diverse and uneven wood structure (Yildirim et al. 2015). Characteristic examples of degradation of the "wood - coating material" composite are shown in Fig. 5.

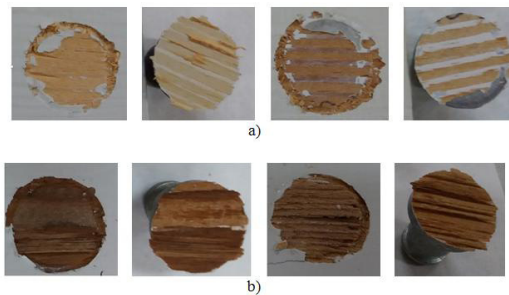


Fig. 5: Degradation options of composite "wood - coating material": a) "mixed" degradation through wood and between wood and coating, b) degradation through wood.

It was obtained that when the degradation was only through the wood, it usually happened through the early wood. This is probably due to the fact that early wood is mostly made of thin-walled elements with a lower density and worse mechanical properties compared to late wood. Examples of such degradation are shown in Fig. 5a. Early wood inserts are characterized by inferior quality of wood, which is commonly used for observation paths and passages.

In all cases of thermally modified wood, this composite "wood - coating material" degraded only through wood (Fig. 5b). This is due to the fact that the tension perpendicular to the grain of thermally modified wood is significantly reduced (Younsi et al. 2010). Fig. 6 shows the dependence of the wood resistance to tension perpendicular to the grain on thermally modifying temperature.

Generally, in the case of oak wood, the wood tension perpendicular increased from 4.5 to 1.8 MPa by increasing the thermally modifying temperature. In the case of pine wood, the range was from 3.5 to 0.2 MPa.

After soaking for 168 hours, the tension perpendicular of thermally unmodified oak and pine fell 5 times (oak) and 7 times (pine). The tension perpendicular of both thermally modified oak and pine wood to the grain, irrespective of thermally modifying temperature varies from 0.2 to 0.3 MPa (Dahle et al. 2017, Ardalany et al. 2011).

After the analysis of the results, it can be said that the difference in tension perpendicular to the grain of the thermally modified and unmodified wood, is significant in case of both types (Fig. 6a,b).

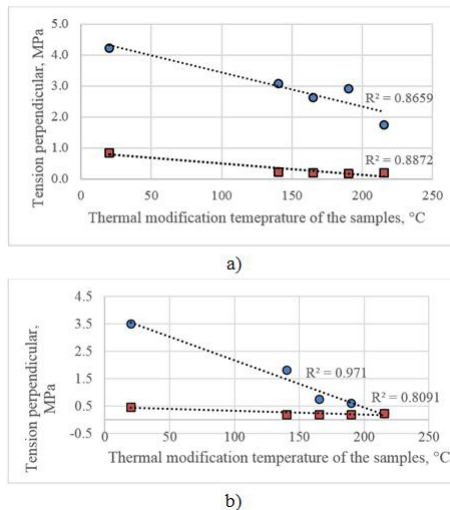


Fig. 6: The dependence of tension perpendicular to the grain on thermal modification temperatures in oak wood (a) and pine wood (b) samples, before soaking, after 168 hours of soaking.

The results of adhesion testing of the mesh cuts of thermally modified coated oak and pine samples at different temperatures and modified at different times indicate that in fact, in all cases, a tier 0 was obtained, i.e. there are no coat splits, which means that the finishing layer is firmly adhered to the wood surface. As the thermal modification temperature increases, the bond strength between the coating material and the coating surface remains stronger than the tension perpendicular of the wood to the grain, except for pine samples that have been thermally modified at 215°C and soaked for one week, when adhesion is reduced (Tier 2: small coat splits in the incision areas, the damage area does not exceed 15%).

Adhesion between the coating material used in the research and the surface of oak and pine wood is strong regardless the thermal modification temperature and soaking time.

During the research it was found that the coating reduces the absorption of unmodified and modified wood several times during short-term moisture, but the difference of absorption of both types of wood, (coated and non-coated) is reduced as the soak time increases.

Resistance of tensile perpendicular to the grain of unmodified and thermally modified coated and non-coated wood samples, under moisture for a long period of time, significantly reduces and becomes approximately equal for all samples. It can be stated that wooden constructions intended to be used in very wet conditions (soil that is not exposed to rain and snow) should be made of thermally modified wood without coating. Thermally modified wood will have greater dimensional and shape stability and biological resistance. Strength in this direction will vary slightly, with mechanical impact; the coating will quickly peel off with a small layer of wood, so the appearance of the wood will soon become much worse than non-coated wood. Thermally treated non-coated wood will perform its functional purpose longer.

CONCLUSIONS

1. Water absorption of thermally modified wood under long-term moisture conditions is lower than that of unmodified wood. Thermally modified wood, is less deformed (pine swell ~ 3%, oak ~ 1%).
2. Water absorption of thermally modified wood with coating is significantly lower than that of non-coated wood, but this difference decreases with the increase of soaking time. At the beginning of the soak, the impregnation of the coated and non-coated oak and pine samples varied about 3 times, and after 168 hours of soaking, varied only 1.5 times.
3. Tension perpendicular of thermally modified dry wood to the grain is significantly less than that of unmodified wood (for oak wood it decreased from 4.2 MPa to 1.8 MPa, for pine wood it decreased from 3.5 MPa to 0.2 MPa). However, after long-term soaking, tension perpendicular of thermally modified and unmodified wood to the grain is significantly reduced (for oak from 0.8 MPa to 0.2 MPa, for pine wood becomes practically the same, in range of 0.2 - 0.3 MPa).
4. The mesh cut method has shown that thermally modified and unmodified wood at all temperatures (140 - 215°C) has good adhesion in the tests when coatings are used. Only the adhesion of the samples with the coating material modified at 215°C slightly deteriorates, therefore it is not appropriate in this case to use coatings.
5. Under wet conditions coated wood only reduces the water absorption of the wood at the initial stage of operation, and then the wood is soaked. The coated layer slows the drying of the wood.
6. Due to reduced resistance of tension perpendicular to the grain, the mechanically exposed coating tears off with the wood layer and may even reduce the service life of the wood.

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