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Insulation Panels Made from Thermally Modified Bark

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Abstract – Thermally treated and ground poplar bark was used as the raw material for pressed bark insulation panels. Bark chips were treated for one, two, and three hours at 180 °C after a slow warming, drying process. The physical and mechanical properties of the pressed panels were investigated and compared to each other and to the control panel made of untreated bark chips. Thermal conductivity showed slight deviations and ranged from 0.064 – 0.067 $W \cdot m^{-1} \cdot K^{-1}$. The MOR and MOE showed a significant increase of 100%. The internal bond increased by 27% while the water absorption and thickness swelling decreased by 53.8% and 69.1% respectively. Panel density did not change significantly because the target density was the same for every panel type. The mechanical and physical properties of thermal insulation panels made of heat-treated chips increased significantly.

thermal insulation / thermal modification / bark panel

Kivonat – Őrölt és hőkezelt nyárfa kéregből készültek hőszigetelő panelek. A kéreg aprítékot szárítás céljából lassan melegítettük 180 °C-ra, majd ezen a hőmérsékleten 1, 2, illetve 3 órán át hőkezeltük. Az elkészült panelek egyes fizikai és mechanikai tulajdonságait a kontrol, kezeletlen anyagból készül panelek tulajdonságaival vetettük össze. A panelek hővezetése kis szórást mutatott: 0,064 – 0,067 $W \cdot m^{-1} \cdot K^{-1}$ értékek között. A hajlító szilárdság (MOR) és a rugalmassági modulusz (MOE) jelentősen (100%-kal) növekedett. A belső kötés (IB) 27%-kal növekedett, míg a vízfelvétel és a vastagsági dagadás 53,8, illetve 69,1%-kal csökkent. A panelek sűrűsége nem változott számottevően, mivel mindig ugyanaz volt a célsűrűség. Összességében a fizikai és mechanikai tulajdonságok kedvezően változtak a hőkezelés hatására.

hőszigetelés / hőkezelés / kéreg panel

1 INTRODUCTION

As most researchers have accepted climate change, reducing energy consumption has become increasingly important. One method for reducing energy demand for buildings is thermal insulation, and many regulations to improve the insulation of buildings have been passed. The EU has set a goal for all new building to be nearly-zero energy buildings the end of 2020. On the one hand, this has led to an increased variety of available building insulation materials. On the other hand, the importance of natural-based, recyclable materials and solutions is increasing and is expected to continue growing in the future as environmental aspects become

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more pressing. Therefore, research focusing on natural-based insulation materials is expanding. Several studies on the insulation of natural materials have been completed including rice husk, sugar cane, coconut fiber, (Panyakaew – Fotios 2008), cotton stalk fibers (Zhou et al. 2010), various grasses (Vėjelienė et al. 2011), papyrus (Tangjuank – Kumfu 2011), pineapple (Tangjuank 2011), jute (Fadhel 2011), oil palm (Manohar 2012), wool (Zach et al. 2012), wood ashes, cotton, animal hair (Rébék-Nagy – Pásztory 2014), plant stalks, textile waste and stubble fibers (Binici et al. 2014) and straw (Volf et al. 2015). The thermal conductivity of insulation made of wood or other plant fibers ranged between 0.037 – 0.065 $W \cdot m^{-1} \cdot K^{-1}$ and similar thermal conductivity was measured by other researchers (Hurtado et al. 2016, Schiavoni et al. 2016, Veitmans – Grinfelds 2016). Bark was also among the investigated materials (Kain et al. 2013, Pásztory – Ronyecz 2013, Pásztory et al. 2017b).

The thermal modification of wood is well known. With heat treatment, dimensional stability and resistance against wood degrading organisms increases, while some strength properties decrease (Seborg et al. 1953, Rowel – Youngs 1981, Hill 2006). Many variables influence the results achieved during heat treatment including tree species, chamber design, treatment duration and temperature, closed or open system, medium, etc. (Rapp 2001, Militz 2002, Hill 2006, Esteves – Periera 2009, Navi – Sandberg 2012, Bak – Németh 2012, Horváth – Csupor 2012, Sandberg – Kutnar 2016).

Boards are heat treated mainly to reduce water uptake and thickness swelling. Lehmann (1964) treated the chips at 204 °C for 15, 30, and 45 minutes and found that particleboard dimensional stability increased slightly, but strength properties decreased. Tomek (1966) studied the heat treatment (1-8 minutes; 230 – 300 °C) of oak chips. The water absorption (WA) and thickness swelling (TS) of the particleboard made from the treated material was reduced; the modulus of rupture (MOR) increased. Lee et al. (2017) investigated the physical-mechanical properties of particleboard made from heat-treated rubber wood (*Hevea brasiliensis* (Willd. ex A. Juss.) Müll.Arg.). Four different temperatures (50, 100, 150 and 200 °C) and three different durations (one, two, three hours) in dry and wet conditions were investigated. The heat treatment of the particles improved the dimensional stability, but mechanical properties decreased with the duration of the heat treatment. Ohlmeyer – Lukowsky (2004) investigated single layer pine particleboard. The particles were treated at 240 °C. The modification decreased the EMC, the WA, and the TS. The internal bond (IB), the MOE, and the MOR of the particleboard decreased as well. Mendes et al. (2013) compared the effect of thermal pre-treatment of strand type particles on the physical-mechanical properties of OSB panels produced from *Pinus taeda* L. The particles were treated at 200 °C and 240 °C. In relation to control panels, thermal treatment of particles at 200 °C negatively affected their physical and mechanical properties, while thermal treatment at 240 °C significantly improved their physical properties and weakened their mechanical properties. Paul et al. (2006) examined the physical and mechanical properties of OSBs made from Scots pine (*Pinus sylvestris* L.) chips treated at 220 °C and 240 °C for 30 minutes, which resulted in decreased thickness swelling and increased dimensional stability. The pre-treatment left the internal bond strength unaffected and greatly reduced the bending properties (MOE, MOR). Boonstra et al. (2006) investigated a two-stage steam pre-treatment (with temperatures below 200 °C) of particleboard made of Norway spruce (*Picea abies* (L.) H. Karst.) and Scots pine (*Pinus sylvestris* L.) chips. The WA and TS decreased, as did the IB. Kwon – Ayrilmis (2016) investigated the physical and mechanical properties of flakeboard made of heat-treated flakes (at 150, 170 and 190 °C; 2 hours). The TS, WA, MOR, MOE decreased as temperature increased, while IB strength increased.

Sometimes thermal post-treatment was used, but steam injection and post-treatment only work with isocyanate, PMUF, MUF, and phenol-formaldehyde adhesives (Boonstra et al. 2006). The swelling of the heat-treated particleboard decreased in tests by Ernst (1967).

Suchsland – Enlow (1968) reduced the swelling with one to two hours of heat treatment at 218 °C, and the mechanical properties of phenolic bonded particleboard were not adversely affected. Menezzi – Tomaselli (2006) examined the effect of thermal post-treatment on OSB dimensional stability. The thermal treatment was effective and reduced the TS, EMC, but did not affect WA. The longer the treatment, the better the dimensional stability became. Oliveira et al. (2017) evaluated the effect of post-heat treatment on the physical and mechanical properties of MDF panels. The dimensional stability of the MDF increased, but all the thermally treated panels revealed a significant decrease in their MOR and MOE. Ayrilmis et al. (2009) also examined the thermal post-treatment of MDF. The heat treatment improved the TS, but WA and linear expansion properties were adversely affected. The MOR and MOE values decreased with increasing temperature. H'ng et al. (2012) post-heat treated particleboard made of rubber wood (*Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg.) in a laboratory press at 100, 150, and 180 °C for 90, 180, and 270 seconds. The thermal treatment reduced the TS, but the WA was not affected.

Thermal conductivity also decreases with thermal treatment (Kol – Sefil 2011, Korkut et al. 2013, Pásztory et al. 2017a). Sekino – Yamaguchi (2010) reduced the thermal conductivity of their insulation panel made of wood shavings by carbonizing the wood material. Similar processes can occur during heat treatment as the structure and the composition of the wood and bark are similar, but not the same.

The main goal of this investigation was to improve the mechanical properties and examine the thermal insulation property changes of insulation panels made of poplar bark. The secondary goal was to investigate the effect of thermal treatment duration on thermal conductivity and other parameters.

1.1 Abbreviations and symbols

TS	Thickness swelling (%)
WA	Water uptake (wt%)
EMC	Equilibrium moisture content (%)
ρ	Density ($kg \cdot m^{-3}$)
λ	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
MOE	Modulus of elasticity (MPa)
MOR	Modulus of rupture (MPa)
IB	Internal bond (MPa)

2 MATERIALS AND METHODS

2.1 Raw material

In Hungary, 88% of harvested timber are broadleaved species, primarily black locust (*Robinia pseudoacacia* L.) and poplar (*Populus* sp.) (NÉBIH 2016). We studied the 'Pannónia' poplar clone (*Populus* × *euramericana* (Dode) Guinier cv. *Pannónia*), which is widespread in Hungarian plantations and favored by the wood industry because of its advantageous mechanical properties. Bark was collected from a nearby sawmill (TAEG PLC Wood Processing Plant); the bark originated from the base to the first branches of the harvested stems. Inner and outer bark was not separated. The collected bark was hammer ground and dried to 8% moisture content. Particles smaller than 0.5 mm were fractionated from the chips.

2.2 Pre-heat treatment

A custom-made labor chamber was used for the treatment. Since the chamber interior is not airtight from the outside, steam escapes from the system during the treatment and oxygen is present. The system is an open and dry system. The bark chips were heated from room temperature to 95 °C in one hour, from 95 °C to 130 °C in another two hours, and then to the peak temperature of 180 °C top in another 30 minutes. Three different treatment durations (constant temperature) were used which lasted one (T1), two (T2) and three (T3) hours *(Figure 1)*. During cooling, the thermal inertia of the chamber was exploited; hence, the specimens were cooled to 25 °C in about 15 hours. Three panels were produced from each type.

Figure 1. Treated raw materials
(C – control; T1 – one hour treatment; T2 – two hours treatment; T3 – three hours treatment)

2.3 Pressing conditions

A laboratory hot press (Siempelkamp) produced panels of 500 mm × 500 mm × 20 mm with the targeted density of 340 $kg \cdot m^{-3}$. The pressing time was 18 seconds per thickness millimeter, at 180 °C, with a pressure of 2.86 MPa, which was reduced after 120 seconds to 2.00 MPa and after an additional 120 seconds to 1.15 MPa to release steam pressure inside the panel.

2.4 Measurements

The physical and mechanical properties of the panels were examined. The thermal conductivity (λ) of all the panels was measured by a hot plate method. The temperature of the cold side was 5 °C and the hot side was 15 °C, with a mean temperature of 10 °C according to the standard (MSZ ISO 8301). To ensure parallel heat flow perpendicular to the surface of the panel, 15 cm of side insulation was used around the specimens. Before the thermal conductivity measurement, the panel had to reach a steady state, which was determined when the fluctuation of the last per minute measurement was under 0.002 $W \cdot m^{-1} \cdot K^{-1}$. The measuring equipment made one measurement every minute, and the average of the last 100 measurements was accepted as the measured result of the panel. The averages of the three data points collected were taken as the results.

Board moisture content and bulk density (ρ) were calculated from ten samples taken from the panels. The thickness swelling (TS) and water absorption (WA) after immersion in water for 2 and 24 hours were calculated according to European standard EN 317 (1993). Ten 50 mm × 50 mm specimens were weighed and their thicknesses measured with an accuracy of 0.01 g and 0.1 mm, respectively. The samples were stored at 20 °C and 65% relative humidity for seven days before measuring.

Bending strength, modulus of elasticity (MOR, MOE) (EN 310), and internal bond (IB) (EN 319) were tested using Instron 5506, a universal testing machine. The specimens were prepared from different areas of the board and cut according to the EN 326-1 (1994) European standard.

For color measuring a Konica-Minolta CM-2600d spectrophotometer with an 8 mm aperture was used SpectraMagic NX software was used to determine the color coordinates (L*; a*; b*) in the CIELab-system. The positive value range of the a* axis is blue; the negative range is green; the positive value range of the b* axis is yellow; and the negative values are blue. The third axis, L*, is perpendicular to the other two, and the lightness values there were between 0 and 100. Due to the mixed structure of the samples, the measurements were taken at five points on a mat of 2 cm-thick conditioned chips.

The differences between the panels were evaluated with “Statistica 13” software. To find means of different treatment that significantly varied from each other, the Tukey-test was run on the raw data. In this test, the means of every treatment were compared to the means of every other treatment and the difference between the two means was identified if this difference was greater than the expected standard error. On the basis of the differences and the identities of the different variables (MOR, MOE, TS, WA, EMC), the treatments were grouped to identify the similarities and differences between treatments.

3 RESULTS AND DISCUSSION

The density of the bark panels treated for one, two, and three hours and the control were 336, 349, 352, and 336 kg·m^{-3} respectively. The density of the panels treated for three hours (T3) is a little higher, which may be caused by the inhomogeneity of the laboratory scale experiment *(Table 1)*.

The thermal conductivity of the panels was 0.064, 0.065, and 0.067 W·m^{-1}·K^{-1} respectively, and the control panels had 0.067 W·m^{-1}·K^{-1}. Although the thermal conductivity of artificial insulating materials is lower (0.015 – 0.045 W·m^{-1}·K^{-1}), the environmental impact of naturally-based insulation is lower. Solid wood’s thermal conductivity is also relatively low (0.08 – 0.2 W·m^{-1}·K^{-1}) (Touloukian et al. 1971, Glass – Zelinka 2010), but different wood-based panels can achieve even better values (0.05 – 0.08 W·m^{-1}·K^{-1}) (TenWolde et al. 1988, Kamke 1989). The thermal conductivity of the panels studied here is located in the middle of that said range.

The thermal conductivity of wood and wood products is influenced by many factors: density, moisture content, chemical composition, porosity, grain direction, etc. (MacLean 1941, TenWolde et al. 1988, Ragland et al. 1991, Suleiman et al. 1999). Heat can be transferred in such panels by heat bridges between the particles and air convection in large gaps. Because the same weight of treated bark was used to press the panels, there is a similar amount of air gaps in the panels; only density affects this. Conductivity increases with density because the amount of solid content increases with density. Parallel to the increasing density of the studied panels, the thermal conductivity of the panels made of treated bark particles increased. The T1 panels (one hour treatment) had the lowest thermal conductivity and density. The control and the T1 panels had a similar density, but the treated panels had lower thermal conductivity.

Thermal treatment affected the cell walls by changing the molecular structure and relationships of the wall. During the heat treatment, mass loss is detectable in the wood; first the transformation and decomposition of the hemicelluloses takes place. The amount of hydroxyl and carbonyl groups decreases in the cell wall, which allows it to absorb less water. Due to weight loss, small cavities and voids form in the cell wall (Stone – Scallan 1965, Tjeerdsma et al. 1998, Tjeerdsma – Militz 2005, Windeisen et al. 2007, Kocaefe et al. 2008, Mitsui et al. 2008, Yin et al. 2011, Kekkonen et al. 2014, Gao et al. 2019). These processes cause a decrease in thermal conductivity. On the other hand, we produced panels of almost the same density from heat-treated materials. Panels made of heat-treated raw material have lower thermal conductivity at the same density (T1), and reach the value of control panels at about 5% higher density (T3). This shows the heat treatment had an effect on the microstructural and chemical levels, but panel density had a greater impact on the thermal conductivity of the panel than the heat treatment. By using other heat-resistant adhesives and post-manufacture heat treatments of the finished panels, panel density and thermal conductivity could be drastically reduced.

Table 1. The physical and mechanical properties of panels, pre-treated with different durations (T1-T2-T3=one hour – two hour – three hour) and the control (C)

	C	**T1**	**T2**	**T3**
Physical properties				
ρ (kg·m^{-3})	336.80 (± 22.95)	336.40 (± 13.53)	349.78 (±20.73)	352.29 (±12.74)
EMC (%)	8.88 (±0.22)	8.33 (±0.22)	8.44 (±0.21)	7.66 (±0.17)
WA (wt%)	217.89 (±48.0)	185.57 (± 23.58)	123.19 (±25.93)	100.61 (±34.82)
TS (%)	17.67 (±2.84)	10.68 (±2.49)	7.65 (±1.49)	5.45 (±0.72)
Thermal properties				
λ (W·m^{-1}·K^{-1})	0.067 (± 0.004)	0.064 (±0.003)	0.065 (±0.005)	0.067 (± 0.001)
Mechanical properties				
MOR (MPa)	0.54 (±0.17)	0.45 (±0.09)	0.89 (± 0.21)	1.08 (± 0.22)
MOE (GPa)	0.28 (±0.08)	0.22 (±0.03)	0.41 (±0.13)	0.56 (± 0.06)
IB (MPa)	0.037 (±0.014)	0.032 (±0.018)	0.039 (±0.009)	0.047 (±0.014)

The **equilibrium moisture content** (EMC) of the control panel was higher (8.88%) than all of the treated bark panels. The T3 (7.66%) has the lowest EMC. A Tukey-test was completed on the data. The T1 and T2 created a group, and the control and the T3 were in individual groups. As a result of heat treatment, the EMC decreased. With increasing temperature and/or time, EMC decreased (Akyildiz – Ateş 2008, Esteves – Pereira 2009). Heat reduces equilibrium moisture content by degrading the hemicellulos, which is one of the major hygroscopic components of wood, and by degrading and volatilizing extractives or further breaking down other low-molecular weight polymers, and increasing cellulose crystallinity.

The control panels had higher **water uptake** (WA) (217.89%) and **thickness swelling** (TS) (17.67%), than any treated panels. Both the WA and TS decreased parallel with the duration of the treatment. The one-hour treatment caused the smallest decrease (WA: 185.57%; TS: 10.68%), and the three-hour treatment caused the highest (WA: 100.61%; TS: 5.45%). The control and T1 form a group based on the WA, the T2 and T3 form another group based on both the WA and the TS. Wood swelling decreased with increasing treatment times and temperature (Boonstra et al. 2006, Winandy – Smith 2006, Kocaefe et al. 2015). The study of Xiangquan et al. (1997) illustrated that post-treatment of the particleboard manufactured from fast growing poplars is effective to improve dimensional stability. Thickness swelling decreased with increasing time and temperature of the post-heat treatment.

As mentioned above, the chemical structure of the cell walls is modified during the heat treatment, and equilibrium moisture content (EMC), water uptake (WA), and thickness swelling (TS) decreased (Tjeerdsma – Militz 2005; Boonstra, 2006, Akyildiz – Ateş 2008, Esteves – Pereira, 2009, Kol – Sefil 2011, Kocaefe et al. 2015, Pelit et al. 2017). As bio-based (lignocellulose) materials are hygroscopic, they absorb water from the surrounding air. As the thermal conductivity is higher in water than in wood, there are strong correlations between the moisture content and thermal conductivity as well as the moisture content and air humidity of the wood and wood products. Since EMC decreases, the panel will contain less water under the same conditions; consequently, its thermal conductivity will be lower (Kol – Sefil 2011, Palumbo et al. 2016, Pelit et al. 2016, Brischke 2017).

The T1 panels had the lowest **MOR** and **MOE**, (0.45 MPa; 0.22 GPa respectively), but these values are similar to the control panel (0.54 MPa; 0.28 GPa respectively). Parallel to the increasing treatment duration, both MOR and MOE increased. Based on the Tukey-test, C and T1 formed one group, and the T2 and T3 formed two other individual groups. In most cases, panels made of pre-heat treated particles or chips, or panels treated after the manufacturing have lower mechanical properties (MOE, MOR) than the untreated particles, chips, or panels (Seborg et al. 1953, Lehmann 1964, Rowel – Youngs 1981, Ohlmeyer – Lukowsky 2004, Lee et al. 2017, etc.). Tomek (1966) found results similar to ours, but this contradicts the results of the majority of researchers.

If all the properties are examined together (with a Tukey test), the control panel and T1 are often in the same group. T2 and T3 are similar in many aspects and form a group, but in other cases they are significantly different. That is, one-hour treatment (T1) caused a relatively small change in the base material, so it is slightly different from the control, while the ever-increasing treatments (T2 and T3) show increasing changes *(Figure 2)*.

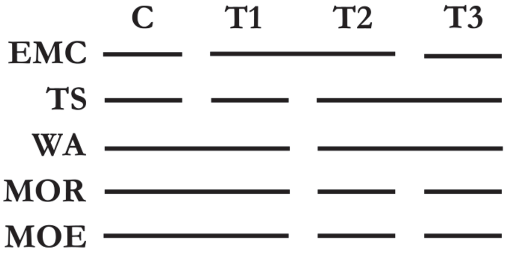

Figure 2. Grouping the treated and control panels based on the Tukey test

The L*, a* and b* **color coordinates** of the untreated chips were 42.46, 13.37 and 36.18 respectively. Parallel with the increasing treatment duration, the lightness obviously decreased, and the red color showed an increasing tendency. The yellow color first increased, but after two and three hours of treatment, it dramatically decreased *(Table 2)*.

Wood color change during heating is mainly due to the chemical transformation of the extracts in the temperature range of 100 – 200 °C. The degree of color change, both in an inert and oxidative atmosphere, increases dramatically between 160 – 180 °C. The lightness of the wood decreases considerably, and its color shifts towards the less saturated, reddish ranges (Németh 1998). As treatment time increases, the rate of change significantly decreases and the color approaches the limit value for each tree species and treatment time. However, a very long treatment time yields the color characteristics obtained at higher temperatures (Németh 1998).

Table 2. CIELab color coordinates of the control and the treated chips

	a*	**b***	**L***
C	13.37	36.12	42.46
T1	16.57	45.26	30.59
T2	20.93	37.30	22.15
T3	23.61	22.33	13.07

In general, insulation boards are not visible in wall construction and there was no purpose for producing visible insulation in this study. However, the degree of treatment is clearly visible and predictable from the measured colors; the small particle pieces are heated faster and more evenly than solid wood.

4 CONCLUSIONS

Heat-treated poplar bark particles are suitable for insulation panels. As described above, it is possible to produce a panel of heat-treated bark particles as the UF adhesive is able to form a bond between the heat treated particles. The effect of heat treatment is hardly perceptible on the mechanical properties of the panels, and the effect of density is stronger: the MOR and MOE of the panels with higher density, even treated for longer periods, are higher.

The thermal conductivity (0.067 $W \cdot m^{-1} \cdot K^{-1}$) of our poplar bark panels lies in the middle of the heat conducting range of other wood-based panels (0.05 – 0.08 $W \cdot m^{-1} \cdot K^{-1}$). The thermal conductivity of these insulation panels made of bark can be reduced by heat treatment. By treating the particles with one hour of heat before the panels are manufactured, the thermal conductivity of a panel – at the same density – decreased to 0.064 $W \cdot m^{-1} \cdot K^{-1}$. In fact, after three hours of treatment, the thermal conductivity of a panel with a density of about 5% is the same as that of the control panel (0.067 $W \cdot m^{-1} \cdot K^{-1}$). That is, by heat treating the particles prior to panel production, the thermal insulation properties of the panels can be improved. A big problem with natural thermal insulation materials is that their moisture content changes in parallel with atmospheric humidity, which strongly influences heat conduction. Pre-manufacturing heat treatment of the raw material bark changes its chemical structure, thus decreasing the water absorption and swelling of the manufactured panels. A three-hour treatment reduced the water uptake to half, decreased the thickness swelling to one-third, and pushed the EMC down 10%. The significantly lower moisture sensitivity is an advantages for practical usage such a treated insulation panel.

The study found that treatment duration affects the changes; the longer treatment at the same temperature causes greater changes in physical and mechanical properties. Color coordinates can help separate the differences caused within the heat-treated bark chips.

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REFERENCES

ABDULLAH, F.A. (2011): Theoretical and experimental investigation of natural composite materials as thermal insulation. Al-Qadisiya Journal For Engineering Sciences 4 (2): 26–36.

AKYILDIZ, H.M. – ATEȘ, S. (2008): Effect of heat treatment on equilibrium moisture content (EMC) of some wood species in Turkey. Research Journal of Agriculture and Biological Sciences 4 (6): 660−665

AYRILMIS, N. – LAUFENBERG, T.L. – WINANDY, J.E. (2009): Dimensional stability and creep behavior of heat-treated exterior medium density fiberboard. European Journal of Wood and Wood Products 67: 287−295. https:/doi.org/10.1007/s00107-009-0311-7

BAK, M. – NÉMETH, R. (2012): Changes in swelling properties and moisture uptake rate of Oil-Heat-Treated poplar (*Populus* × *euramericana* cv. Pannónia) wood. BioResources 7: 5128–5137.

BINICI, H. – EKEN, M. – DOLAZ, M. – AKSOGAN, O. – KARA, M. (2014): An environmentally friendly thermal insulation material from sunflower stalk, textile waste and stubble fibres. Construction and Building Materials 51**:** 24−33. https:/doi.org/10.1016/j.conbuildmat.2013.10.038

BOONSTRA, M.J. – PIZZI, A. – ZOMERS, F. – OHLMEYER, M. – PAUL, W. (2006): The effects of a two stage heat treatment process on the properties of particleboard. Holz als Roh- und Werkstoff 64: 157–164. https://doi.org/10.1007/s00107-005-0055-y

BRISCHKE, C. (2017): Performance of the bio-based materials: Moisture performance (Chapter 5.4) In: JONES D. – BRISCHKE C. (eds.) Performance of Bio-based Building Materials. Woodhead Publishing Series in Civil and Structural Engineering. ISBN: 978-0-08-100982-6

DEL MENEZZI, C.H.S. – TOMASELLI, I. (2006): Contact thermal post-treatment of oriented strandboard to improve dimensional stability: A preliminary study. Holz als Roh- und Werkstoff 64: 212–217. https://doi.org/10.1007/s00107-005-0052-1

ERNST, K. (1967): Möglichkeit zur Verminderung der Quellung bei Spanplatten. Holztechnologie 8: 41–47.

ESTEVES, B.M. – PEREIRA H.M. (2009): Wood modification by heat treatment: a review. BioResources 4 (1): 370–404.

FAO (2015): Forest products 2009-2013. FAO Forestry Series No. 48 FAO Statistics Series No. 204. ISBN 978-92-5-008811-2. http://www.fao.org/3/a-i4746m.pdf

GAO, Y. – XU, K. – PENG, H. – JIANG, J. – ZHAO, R. – LU, J. (2019): Effect of heat treatment on water absorption of chinese fir using TD-NMR. Applied Sciences 9: 78. https://doi.org/10.3390/app9010078

GLASS, S.V. – ZELINKA, S.L. (2010): Moisture relations and physical properties of wood. Wood handbook : wood as an engineering material: Chapter 4. Centennial ed. General technical report FPL; GTR-190. Madison, WI: U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory. pp. 4.1–4.19.

H'NG, P.S. – LEE, S.H. – LUM, W.C. (2012): Effect of post heat treatment on dimensional stability of UF bonded particleboard. Asian Journal of Applied Sciences 5 (5): 299–306. https://doi.org/10.3923/ajaps.2012.299.306

HILL, C. [2006]: Thermal Modification of Wood. In: Hill [2006]: Wood Modification. Chemical, Thermal and Other Processes. John Wiley & Sons, Ltd. ISBN-13 978-0-470-02172-9. pp:99-128.

HORVÁTH, N. – CSUPOR, K. (2012): The protective effectiveness of dry heat treatment on Turkey oak against fugal decay. In: Németh R; Teischinger A. (eds.) (2012): Proceedings of the 5th Conference on Hardwood Research and Utilisation in Europe 2012: „Hardwood Science and Technology". University of West-Hungary, Sopron, Hungary. pp. 362–369

HURTADO, P.L. – ROUILLY, A. – VANDENBOSSCHE V. – RAYNAUD C. (2016): A review on the properties of cellulose fibre insulation. Building and Environment 96: 170–177. https://doi.org/10.1016/j.buildenv.2015.09.031

KAIN, G. – BARBU, M.C. – HINTERREITER, S. – RICHTER, K. – PETUSCHNIGG, A. (2013): Using bark as a heat insulation material. BioResources 8 (3): 3718–3731.

KAMKE, F.A. (1989): Thermal conductivity of wood-based panels. In: Hasselman, D.P.H. – Thomas, J.R. (eds.): Thermal conductivity 20. Proceedings of the Twentieth International Thermal Conductivity Conference, held October 19–21, 1987, in Blacksburg, Virginia. pp. 249-260. ISBN 978-1-4613-0761-7

KEKKONEN, P.M. – YLISASSI, A. – TELKKI, V.V. (2014): Absorption of water in thermally modified pine wood as studied by Nuclear Magnetic Resonance. Journal of Physical Chemistry C 118: 2146–2153. https://doi.org/10.1021/jp411199r

KOCAEFE, D. – PONCSAK, S. – DORÉ, G. – YOUNSI, R. (2008): Effect of heat treatment on the wettability of white ash and soft maple by water. Holz Roh Werkstoff 66: 355–361. https://doi.org/10.1007/s00107-008-0233-9

KOCAEFE, D. – HUANG, X. – KOCAEFE, Y. (2015): Dimensional stabilization of wood. Current Forestry Reports 1(3): 151–161. https://doi.org/10.1007/s40725-015-0017-5

KOL, Ş.H. – SEFIL, Y. (2011): The thermal conductivity of fir and beech wood heat treated at 170, 180, 190, 200, and 212°C, Journal of Applied Polymer Science 121 (4): 2473–2480. https://doi.org/10.1002/app.33885

KORKUT, S. – AYTIN, A. – TAŞDEMÍR, Ç. – GURĂU, L. (2013): The transverse thermal conductivity coefficients of Wild cherry wood heat-treated using the ThermoWood method. ProLigno 9 (4): 649–683. Online ISSN 2069-7430.

Kwon, J.H. – Ayrilmis, N. (2016): Effect of heat-treatment of flakes on physical and mechanical properties of flakeboard. European Journal of Wood and Wood Products 74: 135–136. https:/doi.org/10.1007/s00107-015-0961-6

Lee, S.H. – Ashaari, Z. – Jamaludin, F.R. – Yee, C.N. – Ahamad, W.N. (2017): Physico-mechanical properties of particleboard made from heat-treated rubberwood particles. European Journal of Wood and Wood Products 75: 655–658. https://doi.org/10.1007/s00107-016-1145-8

Lehmann, W.F. (1964): Retarding dimensional changes of particle boards. Information Circular 20, Forest Products Research, Forestry Laboratory, Oregon State University.

MacLean, J.D. (1941): Thermal conductivity of wood. Heating, piping & air conditioning 13 (6): 380–391.

Manohar, K. (2012): Renewable building thermal insulation – Oil Palm fibre. International Journal of Engineering and Technology 2 (3): 475–479.

Mendes, R.F. – Júnior, G.B. – de Almeida, N.F. – Surdi, P.G. – Barberio, I.N. (2013): Effects of thermal pre-treatment and variables of production on properties of OSB panels of *Pinus taeda*. Maderas. Ciencia y Tecnología 15 (2): 141–152. https:/doi.org/10.4067/S0718-221X2013005000012

Mitsui, K. – Inagaki, T. – Tsuchikawa, S. (2008): Monitoring of hydroxyl groups in wood during heat treatment using NIR spectroscopy. Biomacromolecules 9: 286–288. https://doi.org/10.1021/bm7008069

Navi, P. – Sandberg, D. (2012): Thermo-hydromechanical processing of wood. Chapter 9: Heat Treatment. pp. 249–286. EPFL Press. ISBN 978-2-940222-41-1

NÉBIH (2016): Erdővagyon és erdőgazdálkodás Magyarországon 2015. [Forest values and forest management in Hungary in 2015.] https://portal.nebih.gov.hu/documents/10182/206281/2015_leporello_magyar_web_300dpi.pdf/672fd0f8-3a59-4dc7-a51a-13fd0daa7c2f . (in Hungarian)

Németh, K. (1998): A faanyag degradációja. [The degradation of wood.] Mezőgazdasági Szaktudás Kiadó, Budapest. (in Hungarian)

Ohlmeyer, M. – Lukowsky, D. (2004): Wood-based panels produced from thermal treated wood – Properties and Perspectives. Wood-Frame Housing Durability and Disaster Issues Conference. October 4–6 2004, Las Vegas, USA pp. 127–132.

Oliveira, S.L. – Freire, T.P. – Mendes, L.M. – Mendes, R.F. (2017): The effect of post-heat treatment in MDF panels. Materials Research 20 (1): 183–190. https:/doi.org/10.1590/1980-5373-MR-2016-0259

Palumbo, M. – Lacasta, A.M. – Holcroft, N. – Shea, A. – Walker, P. (2016): Determination of hygrothermal parameters of experimental and commercial bio-based insulation materials. Construction and Building Materials 124: 269–275. http://dx.doi.org/10.1016/j.conbuildmat.2016.07.106

Panyakaew, S. – Fotios, S. (2008): Agricultural Waste Materials as Thermal Insulation for Dwellings in Thailand: Preliminary Results. 25th Conference on Passive and Low Energy Architecture, Dublin, 22nd to 24th October:1-6

Pásztory, Z. – Horváth, N. – Börcsök, Z. (2017a): Effect of heat treatment duration on the thermal conductivity of spruce and poplar wood. European Journal of Wood and Wood Products 75: 843–845. https:/doi.org/10.1007/s00107-017-1170-2

Pásztory, Z. – Mohácsiné, R.I. – Börcsök, Z. (2017b): Investigation of thermal insulation panels made of black locust tree bark. Construction and Building Materials 147: 733–735. https:/doi.org/10.1016/j.conbuildmat.2017.04.204

Pásztory, Z. – Ronyecz, I. (2013): The Thermal Insulation Capacity of Tree Bark, Acta Silvatica et Lignaria Hungarica 9: 111–117. https:/doi.org/10.2478/aslh-2013-0009

Paul, W. – Ohlmeyer, M. – Leithoff, H. – Boonstra, M.J. – Pizzi, A. (2006): Optimising the properties of OSB by a one-step heat pre-treatment process. Holz als Roh- und Werkstoff 64: 227–234. https:/doi.org/10.1007/s00107-005-0073-9

Pelit, H. – Korkmaz, M. – Budakçi, M. – Esen, R. (2017): The effects of densification and heat treatment on thermal conductivity of fir wood. The Online Journal of Science and Technology 7(3): 117-122. International Science and Technology Conference, Vienna-Austria, July 13–15, 2016.

RAGLAND, K.W. – AERTS, D.J. – BAKER, A.J (1991): Properties of wood for combustion analysis. Bioresource Technology 37: 161−168.

RAPP, A.O. (ed.) (2001): Review on heat treatments of wood. COST Action E22: Environmental optimisation of wood protection. Proceedings of Special Seminar Antibes, France, 9th February 2001. ISBN: 3 926 301 02 3

RÉBÉK-NAGY, P. – PÁSZTORY, Z. (2014): Természetes anyagok szigetelőképessége. [Thermal performance of natural materials.] Faipar 62: 31−36. https:/doi.org/10.14602/WoodScience-HUN_2014_6 (in Hungarian)

ROWEL, R.M. – YOUNGS, R.L. (1981): Dimensional stabilization of wood in use. Research Note FPL-0243, Forest Products Laboratory, Forest Service, USDA

SANDBERG, D. – KUTNAR, A. (2016): Thermally modified timber: Recent developments in Europe and North America. Wood and Fiber Science 48: 28−39.

SCHIAVONI, S. – D'ALESSANDRO, F. – BIANCHI, F. – ASDRUBALI, F. (2016): Insulation materials for the building sector: A review and comparative analysis. Renewable and Sustainable Energy Reviews 62: 988−1011. https://doi.org/10.1016/j.rser.2016.05.045

SEBORG, R.M. – TARKOW, H. – STAMM, A.J. (1953): Effect of heat upon the dimensional stabilization of wood. Journal of Forest Product Research Society 3 (3): 59−67.

SEKINO, N. – YAMAGUCHI, K. (2010): Carbonizing binderless wood shaving insulation panels for better insulation and durability Part 1: Relationship between thermal conductivity and carbonizing temperature. Proceedings of the International Convention of Society of Wood Science and Technology and United Nations Economic Commission for Europe – Timber Committee October 11−14, 2010, Geneva, Switzerland. Paper IW-3 pp. 8.

STONE, J.E. – SCALLAN, A.M. (1965): Effect of component removal upon the porous structure of the cell wall of wood. Journal of Polymer Science: Part C 11: 13−25.

SUCHSLAND, O. – ENLOW, R.C. (1968): Heat treatment of exterior particleboard. Forest Products Journal 18 (8): 24−28.

SULEIMAN, B.M. – LARFELDT, J. – LECKNER, B. – GUSTAVSON, M. (1999): Thermal conductivity and diffusivity of wood. Wood Science and Technology 33: 465−473.

TANGJUANK, S. – KUMFU, S. (2011): Particle board from papyrus fibres as thermal insulation. Journal of Applied Sciences 11 (14): 2640−2645. https://doi.org/10.3923/jas.2011.2640.2645

TANGJUANK, S. (2011): Thermal insulation and physical properties of particleboards from pineapple leaves. International Journal of Physical Sciences 6 (19): 4528−4532. https:/doi.org/10.5897/IJPS11.1057

TENWOLDE, A. – MCNATT, J.D. – KRAHN, L. (1988): Thermal properties of wood and wood panel products for use in buildings. USDA Forest Sevice DOE/USDA-21697/1

TJEERDSMA, B.F. – 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: 149–153. https://doi.org/10.1007/s001070050

TJEERDSMA, B.F. – MILITZ, H. (2005): Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood. Holz Als Roh-Und Werkstoff 63: 102–111. https://doi.org/10.1007/s00107-004-0532-8

TOMEK, A. (1966): Die Heißvergütung von Holzspänen, ein neues Verfahren zum Hydrophobieren von Spanplatten. Holztechnologie 7: 157−160.

TOULOUKIAN, Y.S. – POWELL, R.W. – HO, C.Y. – KLEMENS, P.G. (1971): Thermophysical and Electronic Properties Information and Analysis Center Lafayette In, TPRC Data Series Volume 2, https://apps.dtic.mil/dtic/tr/fulltext/u2/a951936.pdf retrieved on March 13, 2019

VEITMANS, K. – GRINFELDS, U. (2016): Wood fiber insulation material. Proceedings 22nd Annual International Scientific Conference "Research for Rural Development 2016" 18-20 May, 2016 Vol. 2: 91−98. ISSN 2255-923X

VĖJELIENĖ, J. – GAILIUS, A. – VĖJELIS, S. – VAITKUS, S. – BALČIŪNAS, G. (2011): Evaluation of structure influence on thermal conductivity of thermal insulating materials from renewable resources. Materials Science 17 (2): 208−212. http://dx.doi.org/10.5755/j01.ms.17.2.494

VOLF, M. – DIVIŠ, J. – HAVLÍKA, F. (2015): Thermal, moisture and biological behavior of natural insulating materials. Energy Procedia 78: 1599−1604. https:/doi.org/10.1016/j.egypro.2015.11.219

WINANDY, J.E. – SMITH, W.R. (2006): Enhancing composite durability: using thermal treatments. In: Barnes HM (ed.): Proceed Wood Protection, March 21–23, Forest Prod Society, New Orleans, Louisiana, pp 195−199

WINDEISEN, E. – STROBEL, C. – WEGENER, G. (2007): Chemical changes during the production of thermo-treated beech wood. Wood Science and Technology 41: 523–536. https://doi.org/10.1007/s00226-007-0146-5

XIANGQUAN, Z. – RENSHU, L. – WEIHONG, W. – ANBIN, P. (1997): Heat post-treatment to reduce thickness swelling of particleboard from fast-growing poplars. Journal of Forestry Research 8(3): 188−190. https://doi.org/10.1007/BF02855417

YIN, Y. – BERGLUND, L. – SALMÉN, L. (2011): Effect of steam treatment on the properties of wood cell walls. Biomacromolecules 12: 194–202. https://doi.org/10.1021/bm101144m

ZACH, J. – KORJENIC, A. – PETRÁNEK, V. – HROUDOVÁ, J. – BEDNAR, T. (2012): Performance evaluation and research of alternative thermal insulations based on sheep wool. Energy and Buildings 49: 246−253. https://doi.org/10.1016/j.enbuild.2012.02.014

ZHOU, X. – ZHENG, F. – LI, H. – LU, C. (2010): An environment-friendly thermal insulation material from cotton stalk fibers. Energy and Buildings 42**:** 1070−1074. https:/doi.org/10.1016/j.enbuild.2010.01.020