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THERMAL CONDUCTIVITY OF SPRUCE, BEECH AND OAK HEARTWOOD DEGRADED WITH *TRAMETES VERSICOLOR* L. LLOYD

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ABSTRACT

A new type of bio-based thermal insulation is proposed in this paper. This material is made of wood waste (from wood working manufacture or otherwise non-processable wood) which is intentionally degraded with a white rot fungus. Degradation of wood has an impact on its properties and this impact may be positive for re-purposing the use of such material. The main focus is on thermal properties of this material. A decrease in the values of degraded wood thermal conductivity is described by a fraction of the thermal conductivity value of degraded wood to the value of thermal conductivity of undegraded wood. The fraction for spruce wood was 0.8 in longitudinal direction; 0.64 in radial direction and 0.54 in tangential direction. For beech wood, the fractions were 0.82 for longitudinal direction; 0.61 for radial direction and 0.69 for tangential direction. A decrease in thermal conductivity in oak heartwood was noticeable only in tangential direction; the fraction between thermal diffusivity values was 0.67. The values of thermal conductivity are in good agreement with thermal conductivity values of other bio-based thermal insulation materials.

Key words: degraded wood, thermal insulation, thermal conductivity, thermal diffusivity.

INTRODUCTION

We spend a great amount of time inside buildings and it is therefore important that we feel good during this time. Building materials used for structures play an important role in this. Because the climate in our country has four seasons with fluctuating daily temperatures, it is important to choose a suitable thermal insulating material for these buildings. Conditions and technical requirements for thermal insulation of buildings are very strict and that is why we often choose materials which have the best thermal properties but their other properties related to changes in relative air humidity are not as good.

Thickness and thermal conductivity of a material are used to calculate the thermal insulation of a building. The values of thermal conductivity of the most frequently used insulation materials such as expanded Styrofoam (EPS), extruded Styrofoam or mineral wool are low, around 0.035 $W{\cdot}m^{-1}{\cdot}K^{-1}$ (according to technical documentation by manufacturer ISOVER, 2020). As it was already mentioned, manufacturing of these insulation materials requires a lot of energy and also chemicals. In the past, chlorine and fluor compounds were used as expanding agents in extruded Styrofoam. These compounds contribute to the greenhouse effect. Nowadays, carbon dioxide is used as the expanding agent (SVOBODA *et al*. 2005). Mineral fibers are made by melting a slag-basalt mixture at very high temperatures. The fibers are then created by centrifugal spinning of the molten mixture at a temperature of 1350–1400°C. Melting of the basalt alone and of this mixture is extremely energy-consuming (SVOBODA *et al.* 2005).

Manufacturing of bio-based thermal insulations does not require the use of hazardous chemicals, nor high temperatures. The material is usually grinded into fine fibers, mixed with water and adhesives, filled into forms, eventually pressed and the excess water is evaporated by drying the material. Raw material used for bio-based insulations is waste from other manufactures like wood manufacture or agricultural production. The adhesives are usually natural too or they are harmless compounds. Adhesives used in bio-based thermal insulations are latex, resins or even lignin which is already contained in the raw material itself. Thermal insulation from wood fiber uses ammonium sulphate as fire retardant (STEICO flex038 technical documentation), though it is usually used as fertilizer.

One of the biggest advantages of bio-based thermal insulation is that the raw material is already highly hygroscopic. Hygroscopic materials have the capacity of adsorbing and desorbing water vapor which contributes to moderate extremes of humidity in indoor environments (OSANYINTOLA and SIMONSON 2006, PALUMBO *et al.* 2016, QIN *et al*. 2011, SIMONSON *et al.* 2004). The research by PALUMBO *et al*. (2018) confirmed, that natural materials absorb water immediately after beginning of the experiment. It is important to take this property into consideration as well since water vapors are present inside and outside of buildings all the time. Their movement can affect the performance of materials and foremost the comfortability of spending time in the building. Keeping air humidity at a certain, equilibrium level is important for a healthy living. Hence, natural movement of air humidity inside the material can become an important factor and an advantage in designing buildings.

Bio-based thermal insulations which are available on the market are made of wood fibers (STEICO) and recycled newspaper (blow-in cellulose insulation, STEICO and ISOCELL). Other proposed raw materials for bio-based thermal insulations are hay, corn pith and alginic acid (PALUMBO *et al.* 2018), coniferous tree needles and starch (MUIZNIECE *et al*. 2015, MUIZNIECE and BLUMBERGA 2016), coconut husk (VAN DAM 2004, ALAVEZ-RAMIREZ 2012, PANYAKAEW and FOTIOS 2011), wood saw dust (CETINER and SHEA 2018) and also mycelium (AMSTISLAVSKIJ *et al.* 2017, XING *et al*. 2018).

Another proposed bio-based insulation raw material is wood infested with a wood decaying fungus. Wood decaying fungi decrease the mass of the wood and the wood becomes more porous (REINPRECHT 2008). These properties – low mass and high porosity - are significant for thermal insulations. The main focus of this work was to compare thermal conductivity values of degraded wood species to reference data of thermal conductivity values of undegraded wood species. Thermal conductivity values of degraded wood species were then compared to thermal conductivity values of other bio-based thermal insulations, available on the market and also experimental ones.

MATERIALS AND METHOD

Three wood species were chosen for this experiment. The researched wood species are the most widespread species in Slovakia (Zelená správa za rok 2019 - MORAVČÍK *et al.* 2020). From coniferous trees, it is spruce (*Picea abies*, L.). Among deciduous trees species it is beech (*Fagus sylvatica,* L.) and oak (*Quercus petraea,* Matt. Liebl.), its heartwood part was used for the experiment. The different wood species were also chosen to compare the effect of degradation on thermal properties. Spruce wood was provided by a wooden window frames manufacturer and beech and oak heartwood lumber was stored at the Department of Wood Science. The samples were cut and sanded to a size of 50 × 50 × 8 mm. The smallest dimension of the sample was cut accordingly to each anatomical direction on wood. A total of 8 samples per anatomical direction per wood species were used for thermal properties measurement. The size of the samples was limited by the dimensions of the Kolle flasks. These dimensions were also determined by preliminary calculations of the thermal field in wood according to literature (HRČKA and BABIAK 2017).

The intentional degradation was performed in the laboratory of Department of Wood Technology. Kolle flasks were sterilized in an autoclave prior to the experiment. A malt extract (prepared accordingly to STN EN 113) was poured into the Kolle flasks and it was inoculated with growing fungal cultures. The fungus was incubated until the surface of the malt extract was fully covered with mycelia growth. The samples were submerged in distilled water for 24 hours prior to the degradation experiment. Four or five samples were placed into one Kolle flask. Each sample was placed on a "U" shaped stainless steel support. Duration of the intentional degradation was 6 months. This duration was chosen according to results from a similar experiment (SLOVÁČKOVÁ *et al.* 2018). After the time has passed, the samples were taken out of the Kolle flasks and cleaned off of visible mycelium remnants. The samples were then submerged in distilled water. Submerging caused all air inside the sample to escape and this gradually stopped activity of the fungus. Wood decaying fungi need an air content of at least 5–20 % to be able to survive in wood (RYPÁČEK 1957). Each wood species was put into a separate container. The distilled water was changed gradually, once in every two weeks. The samples were kept in water until they reached a maximum moisture content. The maximum moisture content was checked regularly by weighing the samples.

After the samples reached the maximum moisture content, they were taken out of the distilled water and put into an air-conditioning chamber (A/C chamber, Binder, model KBF 780, Tuttlingen, Germany) at an air temperature of 20 ± 2°C and a relative air humidity of 60 ± 3%. When the samples reached the maximum moisture content, their dimensions were measured with a slide caliper (Mitutoyo Absolute Digimatic) and their masses were determined (laboratory scale RADWAG, Analytical Balances, model XA 60/20/X, accuracy $1 \cdot 10^{-5}$ g).

Thermal properties were measured and calculated according to a method proposed by HRČKA and SLOVÁČKOVÁ (2019). Four samples with two heating foils and three thermocouples and a pyrometer were assembled in a fixed position (according to scheme 2; HRČKA and SLOVÁČKOVÁ 2019). Position of the thermocouples was fixed with a cellulose based scotch tape. The calculation was created in MS Excel Visual Basic for Applications and the Solver add-in program of MS Excel according to the equation proposed by HRČKA and BABIAK (2017).

The equation is solved as an 3-dimensional problem. Data needed to find the solution are gathered from measuring of the temperature change during a period of time (one hour per run) with the three thermocouples and the pyrometer. Thicknesses of the samples were also determined and their densities were calculated. The performance of the heating foil is also needed for the calculation, this was determined by Ohm´s equation. The final solutions of the equation are thermal conductivity, thermal diffusivity and specific heat capacity for all anatomical directions in wood. Because the measurement and evaluation of the results take a considerable amount of time, a follow-up experiment with undegraded wood was not performed. The results of thermal properties of undegraded wood done with this same method were published in other works (HRČKA and BABIAK 2017; SLOVÁČKOVÁ *et al.* 2018), so these data were used as reference data.

The 8 degraded samples were randomly divided into two sets, four samples each, for measuring thermal properties. Due to the level of degradation, only one full set of four samples was possible for some groups of samples (the second set of longitudinal and radial direction groups of spruce wood contained only three samples). In these sets, the missing sample was always substituted by randomly choosing one sample from the full set.

RESULTS

Medians of thermal conductivity values (λ), thermal diffusivity values (a) and specific heat capacity values (c) of the researched degraded wood species measured at their equilibrium moisture content reached at the air temperature of 20 ± 2°C and relative air humidity of 60 ± 3% are presented in Table 1. Equilibrium moisture contents reached at these conditions were 15.2% for degraded spruce wood, 15.0% for degraded beech wood and 14.9% for degraded oak heartwood. It must be noted, that these moisture contents were reached in the process of desorption and they are higher by approximately 2.5 % than moisture contents reached in the process of sorption. Densities of the degraded samples were 242.9 $kg \cdot m^{-3}$ for spruce wood, 375.4 $kg \cdot m^{-3}$ for beech wood and 523.8 $kg \cdot m^{-3}$ for oak heartwood. Thicknesses of the measured samples were 7.64 mm for spruce wood, 8.29 mm for beech wood and 7.78 mm for oak heartwood.

Tab. 1 Medians and quartiles Q1 and Q3 of thermal conductivity values, thermal diffusivity values, specific heat capacity for all anatomical directions of the researched wood species.

Wood species	Anatomical direction	Thermal conductivity $[W \cdot (m \cdot K)^{-1}]$	Thermal diffusivity $[m^2 \cdot s^{-1}]$	Specific heat capacity $[kJ \cdot (kg \cdot K)^{-1}]$
Degraded spruce	L	0.28 (0.27 to 0.28)	$6{,}97 \cdot 10^{-7}$ ($6.82 \cdot 10^{-7}$ to $7.13 \cdot 10^{-7}$)	1.48 (1.43 to 1.55)
	R	0.09 (0.08 to 0.10)	$2{,}50 \cdot 10^{-7}$ ($2.33 \cdot 10^{-7}$ to $2.88 \cdot 10^{-7}$)	
	T	0.07 (0.07 to 0.07)	$2{,}15 \cdot 10^{-7}$ ($1.99 \cdot 10^{-7}$ to $2.22 \cdot 10^{-7}$)	
Degraded beech	L	0.31 (0.31 to 0.33)	$6{,}69 \cdot 10^{-7}$ ($6.05 \cdot 10^{-7}$ to $7.46 \cdot 10^{-7}$)	1.35 (1.24 to 1.40)
	R	0.14 (0.13 to 0.15)	$2{,}75 \cdot 10^{-7}$ ($2.40 \cdot 10^{-7}$ to $2.99 \cdot 10^{-7}$)	
	T	0.11 (0.10 to 0.11)	$2{,}13 \cdot 10^{-7}$ ($1.91 \cdot 10^{-7}$ to $2.35 \cdot 10^{-7}$)	
Degraded oak heartwood	L	0.35 (0.34 to 0.35)	$4{,}81 \cdot 10^{-7}$ ($4.29 \cdot 10^{-7}$ to $5.34 \cdot 10^{-7}$)	1.32 (1.23 to 1.39)
	R	0.20 (0.20 to 0.21)	$2{,}65 \cdot 10^{-7}$ ($2.55 \cdot 10^{-7}$ to $2.71 \cdot 10^{-7}$)	
	T	0.14 (0.13 to 0.15)	$2{,}46 \cdot 10^{-7}$ ($1.95 \cdot 10^{-7}$ to $2.70 \cdot 10^{-7}$)	

It is apparent, that the values of λ are the highest in longitudinal direction and the lowest in tangential direction. Degraded spruce wood reached the lowest values of λ from all researched wood species. It seems that the low density and high porosity of degraded spruce wood were significant factors influencing the values of λ.

The a values in transversal directions of degraded wood are in a similar range. The a value in longitudinal direction of degraded oak heartwood is lower than the a values in longitudinal directions in the other two wood species. Degraded spruce and beech wood reached a similar value of a in longitudinal direction. Thermal diffusivity is defined as the ratio of λ to the product of density and c. Hence, a conclusion on the density itself influencing the values of a is not possible to state without taking the influence of c and λ on thermal diffusivity into consideration as well. As it was similarly stated by GLASS and ZELINKA (2010), conclusions regarding the thermal diffusivity variation with temperature and density are often based on calculating the effect of these variables on heat capacity and thermal conductivity.

All degraded wood species reached a value of specific heat capacity within a similar range despite having different densities. Specific heat capacity does not depend on wood species. It depends on temperature and moisture content of wood (GLASS and ZELINKA 2010).

Thermal conductivity values of degraded spruce wood are lower than in undegraded spruce wood. The λ values of undegraded spruce wood were 0.35 $W \cdot (m \cdot K)^{-1}$ in the longitudinal direction; 0.14 $W \cdot (m \cdot K)^{-1}$ in radial direction and 0.13 $W \cdot (m \cdot K)^{-1}$ in tangential direction (SLOVÁČKOVÁ *et al.* 2018). These values were determined at an air temperature of 20 ± 2°C and relative air humidity of 65 ± 3%.

λ values for degraded beech wood are also lower than in undegraded beech wood. The λ values for undegraded beech wood were (determined at an air temperature of 20 ± 2°C and a relative air humidity of 65%): 0.38 $W \cdot (m \cdot K)^{-1}$ in the longitudinal direction; 0.23 $W \cdot (m \cdot K)^{-1}$ in radial direction and 0.16 $W \cdot (m \cdot K)^{-1}$ in tangential direction (HRČKA and BABIAK 2017). Hrčka and Babiak also stated ***a*** values of undegraded beech wood: $2.9 \cdot 10^{-7}$ $m^2 \cdot s^{-1}$ in longitudinal direction; $1.7 \cdot 10^{-7}$ $m^2 \cdot s^{-1}$ in radial direction and $1.2 \cdot 10^{-7}$ $m^2 \cdot s^{-1}$ in tangential direction. These values are lower than ***a*** values of degraded beech wood which means that degraded beech wood reacts to temperature changes faster than undegraded wood.

Degraded oak heartwood has similar λ values as undegraded oak wood. The λ value in longitudinal direction was 0.348 $W \cdot (m \cdot K)^{-1}$; 0.200 $W \cdot (m \cdot K)^{-1}$ in radial direction and 0.21 $W \cdot (m \cdot K)^{-1}$ in tangential direction (POŽGAJ *et al.* 1997). Only the λ value in tangential direction of degraded oak heartwood was lower compared to the λ value in tangential direction of undegraded oak wood. Varying porosity of the oak heartwood samples is suggested as one of the factors which caused a decrease in the value of λ only in tangential direction. The samples used for measuring thermal properties in tangential direction had a lower average porosity by approximately 6% than the samples used for measuring thermal properties in longitudinal and radial direction.

DISCUSSION

λ values of various other bio-based thermal insulations are listed in table 2. The values of existing thermal insulations available on the market and also experimental bio-based thermal insulations are presented. All values were measured at similar conditions; an air temperature of 20 ± 2°C and relative air humidity of 50–65%.

Tab. 2 λ values of various bio-based thermal insulations. Thermal insulations available on the market are divided from experimental materials.

Type of insulation	Thermal conductivity $[W \cdot (m \cdot K)^{-1}]$	Source
STEICO flex038	0.038	Technical documentation of STEICO flex038 product, 2020
Blow-in cellulose (ISOCELL, STEICO)	0.038	Technical documentation of Blow-in cellulose product, 2020
Coconut husk + bagasa	0.048–0.068	PANYAKAEW, FOTIOS (2011)
Needles of coniferous trees	0.0562–0.0654	MUIZNIECE *et al.* (2015)
Saw dust	0.0568–0.0629	CETINER and SHEA (2018)
Corn pith and alginic acid	0.042; 0.048	PALUMBO *et al.* (2018)
Mycelium	0.078–0.081	XING *et al.* (2018)
	0.05–0.07	AMSTISLAVSKIJ (2017)

Based on the values listed in Table 2., it is possible to conclude that the λ values of bio-based thermal insulations are in a similar range. The λ value of degraded spruce wood in tangential direction comes the closest to λ values of other bio-based thermal insulations. It is necessary to note, that the samples measured in the experiment in this paper were all solid whereas the materials listed in Table 2. were measured in an disintegrated state and made into a board.

Higher λ values may be caused by the influence of moisture on thermal properties of wood. Thermal conductivity value increases with increasing moisture content of wood (GLASS and ZELINKA 2010). Considering that raw materials for bio-based thermal insulations are highly hygroscopic and they absorb moisture immediately (PALUMBO *et al.* 2018), the fact that moisture content influences λ values must be taken in account.

Materials absorb water differently. Their moisture content at the same relative air humidity can differ. Inorganic materials are also able to absorb water. As it was proven in the research by Palumbo *et al*. (2018), extruded Styrofoam did not absorb water until relative air humidity reached 80% and then absorbed water abruptly, 4% at once. The absorption continued slowly until the material reached a 7% moisture content. The research by LI *et al*. (2020) showed, that polyphenolic insulation material reached a moisture content of 6% at a relative air humidity of 65%. Polyurethane insulation material reached a moisture content of only 1.5% at the same relative air humidity.

The equilibrium moisture contents of the materials listed in Table 2 were: at a relative humidity of 65% - wood wool w = 8%; corn pith w = 10% (PALUMBO *et al.* 2018; saw dust w= 6.5–6.8% (CETINER and SHEA 2018). Equilibrium moisture contents of the samples used in our experiment reached at relative air humidity of 60% were: degraded spruce wood w = 15.2%; degraded beech wood w = 15.0% and degraded oak heartwood w = 14.9%. The experiment was performed in a desorption process, that is why the equilibrium moisture contents are slightly higher. Equilibrium moisture contents of the samples reached at the same relative air humidity but in the process of sorption were: 13.3% in degraded spruce wood; 12.3% in degraded beech wood and 11.9% in degraded oak heartwood. The difference in the moisture contents is small, but it may have had a small impact on the final values of degraded wood´s thermal properties presented in Table 1.

CONCLUSION

The main focus of this work was thermal conductivity of wood degraded with the white rot fungus *Trametes versicolor*. The experiment was performed on three wood species – spruce, beech and oak heartwood. The values of λ in degraded spruce and beech wood conditioned at relative air humidity of 60 ± 5 % were lower than λ values of undegraded spruce and beech wood. In degraded oak heartwood, only the λ value in tangential direction was lower than the λ value of undegraded oak heartwood. To compare the decrease in thermal conductivity values, ratios of degraded and undegraded thermal conductivities are presented: longitudinal direction in spruce 0,8; radial direction 0,64; tangential direction 0,54. The ratios for beech wood are as follows: λ ratio of degraded and undegraded wood for longitudinal direction 0,82; for radial direction 0,61 and 0,69 for tangential direction. The ratio for oak heartwood in tangential direction is 0,67.

The λ values of degraded spruce wood in tangential direction come close to λ values of experimental bio-based thermal insulations. It is important to note that values of thermal properties presented in this paper were measured in the process of desorption and the moisture content of the material was slightly higher than in the process of sorption which could have had an influence on the final values.

Bio-based thermal insulations are a suitable ecological alternative to inorganic thermal insulations. The λ values of bio-based thermal insulation are slightly higher than λ values of inorganic thermal insulations, but they have few advantages. The main advantage is, that the raw material for their production can be planted and raised and the manufacturing of these materials has a minimal impact on the environment.

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