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Hygrothermal properties of advanced bio-based insulation materials

Filip Fedorik [a,*], Jiri Zach [b], Marja Lehto [c], Hanna-Riitta Kymäläinen [d], Risto Kuisma [d], Marja Jallinoja [c], Kimmo Illikainen [e], Sanna Alitalo [e]

[a] University of Oulu, P.O.Box 8000, FI-90014 Oulu, Finland
[b] Brno University of Technology, Faculty of Civil Engineering, Veveří 512/95, Brno 602 00, Czech Republic
[c] Natural Resources Institute Finland (Luke), Latokartanonkaari 9 FI-00790, Finland
[d] Department of Agricultural Sciences, University of Helsinki, P.O. Box 28 FI-00014, Finland
[e] School of Engineering, Oulu University of Applied Sciences, P.O. Box 222, FI-90101 Oulu, Finland

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ABSTRACT

Hygrothermal performance of buildings is one key element to the sustainable design, health, and comfort of the indoor environment. Building sustainability depends on all associated lifespan stages, from building design and material production to demounting and waste management. Many building materials are unsustainable in terms of their environmental impacts. One approach to reduce environmental impacts associated with buildings is the development and application of bio-based building materials. The aim of this study was to determine the hygrothermal properties of bio-based thermal insulators that promote energy efficiency and contribute in decreasing environmental impacts of buildings. Here, the hygrothermal properties of eight new peat-, recycled paper-, wood shaving-, and feather-based insulation materials were assessed. Measurements of these material properties will improve understanding of the energy efficiency, permeability, and sustainability of new buildings, building retrofits, or both. Data on these new materials will provide the necessary parameters to develop a hygrothermal dynamic numerical model. The studied bio-based materials appear to provide sufficient hygrothermal performance, which is comparable with conventional insulation materials with minimum embodied energy.

1. Introduction

Current development in the building sector emphasizes the need for energy-efficient designs and materials to minimize the environmental and economic impact of buildings. Energy consumption in buildings accounts for approximately 40% of all energy use in the European Union [1]. Reducing carbon footprint is a key motivator for the building industry in developing new strategies of designs and resources. New designs address all processes associated with construction to provide sustainable buildings. For instance, material production must consider transport, embodied energy, and material sources. During construction, site waste management and recycling must be also well organized. Energy sources and use, water and waste management, and including maintenance (optimum efficiency of the functions that service a building) are required during the lifespan of a building. At the end of the building lifespan, processes associated with demounting, such as waste management (e.g. recycling, landscape) must be considered. Materials used in buildings have diverse environmental impacts during the building's lifecycle, such as the impacts associated with extraction of the raw material, transportation, processing, construction, use, demounting, and manipulation of waste material. Low-energy building designs require thick layers of insulation materials to provide high thermal resistance of building envelopes [2]. Due to the environmental impacts of conventional insulators, interest in the use of bio-based insulation materials has increased. Sustainability is a broad concept [3]. In the context of this study features of sustainability of bio-based materials include abundance and local availability, recyclability, biodegradability, renewability, and cost. Such bio-based insulations contribute to energy savings and building sustainability by their embodied energy, depletion, and waste generation [4].

Due to their impact on hygrothermal performance of a building envelope, insulation material is a key aspect of low-energy buildings and a healthy indoor environment, both in new and retrofit constructions. A wide range of conventional thermal insulation materials are currently available that provide sufficient thermal resistance. These include glass wool (GW), mineral wool (MW), phenolic foam (PF), polyurethane foams (PU), expanded polystyrene (EPS), and extruded polystyrene (XPS). MW and EPS are the

* Corresponding author.
E-mail address: filip.fedorik@oulu.fi (F. Fedorik).

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most used insulation materials in the building industry in Europe [5]. However, MW remains underutilized as a recycling material and its waste volume increases annually [6]. The PU foam recycling process is usually physical, chemical, or based on biodegradation. However, none of these options provide a consistent, high-quality, re-usable product [7], such as bio-based materials that can be recycled.

Research in developing bio-based building materials is of importance, as these materials offer promise as sustainable insulating materials due to its reduction of embodied energy in comparison to conventional insulators and other features of sustainability mentioned, e.g. biodegradability. Nonetheless, materials cannot be used in buildings unless the material's hygrothermal properties are appropriately functional and sustainable. Thermal insulation products can be derived from natural fibers, such as wood, hemp, and flax, which have thermal properties that are comparable with materials such as EPS [8] and other conventional insulations [9]. However, the thermal properties of hemp, flax, and peat depend on the mechanical processing method and density of the material [10]. Sufficient thermal insulators can be also made of bamboo fibers and different bio-glues by thermo-pressing [11], or by using wheat straw wastes as aggregate and geopolymer as binder [12], or from larch bark [13]. Furthermore, bio-based materials are sensitive to microbial growth, which may lead to material degradation and poor quality of the indoor environment. Therefore, it is important to process these materials carefully throughout their lifespan to avoid excessive moisture and contact with free water [9].

Here, the hygrothermal properties of new thermal insulation products manufactured from natural sources were assessed. Peat is an accessible source of a raw material in Finland, with peatland and land area covered with peat of varying thickness estimated to encompass approximately 90 000 km^2 (or about 27.6% of the country's area) [14]. Peat is formed by decomposition and fragmentation of diverse plants (mostly moss) and has been mainly used for energy production to replace fuels such as coal, gas, or oil [15]. The material properties of peat have been studied primarily from the perspective of subsoil as material-imposed loads from civil-engineering projects [16]. Recently, material qualities of peat have been evaluated for use in developing bio-based products, such as thermal insulation in the building sector [17]. Peatlands in Boreal regions are dominated by different species of bryophytes (mosses), such as those of *Sphagnum* [18]. *Sphagnum* moss represents a renewable growing media, as harvesting < 30 cm from a bed of *Sphagnum* moss would lead to an approximately 30-year harvesting cycle [19]. Due to its accessibility and abundance, *Sphagnum* moss and peat represent a potential useful source of building insulation material in Finland, and presumably also in other locations that are rich in peatlands [17,20]. Peat has been mentioned as an environmentally friendly raw material of thermal insulations in construction [e.g. [17]], but the sustainability of peat has also been questioned particularly in the energy sector [15].

The forest industry plays a significant economic role in Finland. Forestry land covers over 80% of the total area of Finland, of which about 65% is forest (ClimateChangePost, https://www.climatechangepost.com/). The forest industry covers about 2/3 of total production value for pulp and paper in Finland (Finnish Forest Industries, www.forestindustries.fi). Wood is a renewable, sustainable, and natural building material. Wood waste represents approximately $50 \cdot 10^6$ m^3 per year in the European Union [21]. Wood waste is used for energy recovery, recycling, or in a landfill [22], and recycled wood waste is emerging as a promising resource for building materials. For instance, wood waste from pallet wood can be used as a substitute for spruce in wood wool cement boards because of their similar microstructure [23]. A byproduct of sawn wood production represents a source of raw bio-material applicable as thermal insulation in buildings, such as wood chips. Wood-based thermal insulations in building retrofits have the potential to support high lifecycle net CO_2-eq emission saving compared with conventional materials such as glass wool [24]. One of the final products of wood processing is paper. Approximately 93 million tons of paper and paperboard were consumed in Europe in 2016. Therefore, waste of the pulp and paper industry may be a potential source of recycling to further decrease the environmental impacts by reduction of raw material depletion [25]. For instance, the waste from pulp and paper has been used to improve thermal properties of bricks [26], as admixture for cement composites [27], or as loose-fill insulation material made of milled paper [28].

In addition to plant-based materials, bio-based materials derived from certain animals may have unique thermal properties. Most notably, a potential material could be chicken feathers. Approximately 65 million tons of chicken feathers are generated annually globally [29]. In the EU, approximately 3.1 million tons of chicken feathers (with some 10 000 tons produced in Finland) are estimated to be generated annually [30,31]. Chicken feathers are lightweight, porous, hydrophobic, and consist of approximately 91% keratin, 1% lipids, and 8% water [32]. Due to the diverse microbes (i.e. bacteria, fungi) associated with feathers, this material must be treated with antimicrobials to prevent microbial growth inside building structures [33]. Most poultry feathers are disposed of, used in landfills, or incinerated. Only a minor proportion of this resource is recycled, for example as a low-nutritional-value animal food or as a textile insulation material [32,34]. Uncontrolled disposal of poultry feathers is environmentally unfriendly, as the main method of disposal is incineration, which has high energy consumption and yields large carbon emissions [33]. While utilizing feather-based products is limited by difficulties in processing this material (e.g. in dissolving feathers due their high level of crosslinking [35]), new approaches to processing feathers are promising for new industrial applications [31,36].

Potential energy efficiencies of buildings should be analyzed in advance to determine whether the materials and structural design provide suitable hygrothermal performance. All layers of structural assemblies must be chosen with respect to the others to provide a functioning building envelope. The assessment of hygrothermal performance of the assemblies is usually provided by numerical simulation, the accuracy of which significantly depends on material properties. The objective of the present research is to determine the hygrothermal material properties of the following eight bio-based materials that can be used as thermal insulators: two materials derived from peat, two from a mixture of peat and sphagnum moss, one from sphagnum moss, one from wood chips, one from recycled paper, and one from chicken feathers.

2. Materials and methods

2.1. Bio-based materials, origin, and form

Thermal insulation materials derived from peat (PE1 and PE2), *Sphagnum* moss (MO), a mix of peat and *Sphagnum* moss (PS1 and PS2), wood shavings (WO), recycled paper/paper wool (PW), and feathers (FE) were investigated (Fig. 1). The peat- (PE1 and PE2), peat and *Sphagnum* mix- (PS1 and PS2), and moss- (MO) based insulations were under development and thus had not been commercialized yet. The difference between PS1 and PS2 is in the ratio of peat and *Sphagnum* moss. The loose materials (PE2, MO, WO, and FE) contained mostly processed raw material. Insulations in form of boards (PE1, PS1, PS2, and PW) contained about 85% raw natural material and 15% plastic binder (PES bicomponent fibers) (Table 1). In case of loose-fill insulation (MO, WO, FE), particles with size up to 32 mm were used. Test materials were in two forms

Fig. 1. Raw bio-based materials of investigated insulators.

Table 1
Origin, composition and form of bio-based thermal insulation materials examined.

Code	Raw material	Raw material [%]	Biocomponent fibers [%]	Form of insulation	Origin/production of the material
PE1	Peat	85	15	board	Peatland, harvested
PE2	Peat	100	0	loose	Peatland, harvested
PS1	Peat and *Sphagnum* mixture	85	15	board	Peat and *Sphagnum* moss mix, harvested
PS2	Peat and *Sphagnum* mixture	85	15	board	Peat and *Sphagnum* moss mix, harvested
MO	Moss	100	0	loose	*Sphagnum* moss, harvested
WO	Wood shavings/cutter chips	100	0	loose	By-product of sawn wood production
PW	Paper wool	85	15	board	Recycled paper
FE	Feather	100	0	loose	Chicken feather, crushed and washed

as insulation boards (produced by air-lay technology with utilization of bicomponent PES fibers and as loose-fill insulations) (Table 1). To screen the potential thermal properties, in this study the materials were examined as such without special additions (e.g. fire retardants) during production process.

2.2. Hygrothermal material properties measurement of bio-based insulators

The following key physical and hygrothermal properties (key parameters for dynamic hygrothermal simulation) were determined for the test specimens:

Linear dimensions *a, b* [mm] and thickness *t* [mm] according to EN 822 [37] and EN 823 [38],
Density according ρ_s [kg/m^3] to EN 1602 [39],
Specific heat $c_{p,s}$, [J/(kg.K)] according to EN ISO 11357-4 [40],
Sorption and desorption moisture properties u [%] according to EN ISO 12571 [41],
Factor of diffusion resistance $\mu(\varphi)$ [-] according to EN ISO 12572 [42],
Thermal conductivity λ [W/(m.K)] measurements according to EN 12667 [43] and ISO 8301 [44].

In case of loose-fill insulators, test samples were created with support frames from thin plastic boards (final value of thermal conductivity was in each case corrected for the effect of the frame).

The size of the test specimens corresponded to the requirements of the individual test standards and the production thicknesses of the individual materials. In the case of loose-fill insulators, the size 200 × 200 × 38 mm was chosen. For the PW sample, the largest size 600 × 600 mm had to be selected (due to the sample thickness of 100 mm). For the other samples, a body size of 300 × 300 mm was chosen (unless another specific sample size was required for the given test).

2.2.1. Linear dimensions and thickness

Linear dimensions and thickness of test samples were determined according to EN 822 and EN 823 for samples conditioned under labor conditions (temperature 23 °C, relative humidity 50%). In case of board insulation, an additional press of 50 Pa (as a standard according to EN 823) was used.

2.2.2. Bulk density and porosity

Bulk density is an indispensable property for evaluating the dynamic hygrothermal performance of a building component. Bulk density was determined by a gravimetric method after drying the specimens at 105℃. Dimensions and weights of the specimens were measured with accuracy of 0.1 mm and 0.01 g, respectively. The bulk density was determined according to EN 1602 [39] for materials conditioned under labor conditions (temperature 23 °C, relative humidity 50%). Porosity was determined for dry state of samples with utilization of a standard helium pycnometer.

2.2.3. Thermal conductivity

Thermal conductivity λ [W/(m.K)] is a fundamental material property that describes the ability of a material to transfer heat by conduction. Thermal conductivity of building insulation materials depends on moisture content and temperature. Thermal conductivity was measured dependent on dry and moist state and on main temperature.

For determination of thermal conductivity, test samples with three types of dimensions were used (according to thickness of each type of samples):

plates 200 × 200 × 38 mm for loose-fill insulators,
plates 600 × 600 mm for PW samples (by 100 mm of thickness)
plates 300 × 300 mm for all other samples.

Thicknesses of test samples varied from 38.1 to 100.0 mm (Table 2). Thermal conductivity was determined according to EN 12667 [43] and ISO 8301 [44]. Standard conditions for measurements were 10 °C for mean temperature and 10 °C for temperature difference.

2.2.4. Specific heat capacity

Dynamic hygrothermal performance of building elements depends on a specific heat capacity c_p [J/(kg.K)] of the applied materials. The specific heat capacity determines the ability of a material to store heat in relation to its weight. The specific heat capacity was measured according to EN ISO 11357-4 [40] using the differential scanning calorimetry (DSC) method on three samples for each insulation material. The measurement was performed on small samples (≃6x6x6 mm), which were prepared from insulators by gradual homogenization and quaternation of the homogenized material.

2.2.5. Water vapor resistance factor

The ability of a building material to resist water vapor diffusion is expressed by the water vapor resistance factor μ [-]. The measurement was provided according to EN ISO 12,572 [42]. The water vapor resistance factor μ represents the ratio of the water vapor permeability of air δ_a and construction material δ as following:

$$\mu = \frac{\delta_a}{\delta}$$

where

$$\delta_a = \frac{0.086 \cdot p_0}{R_D \cdot T \cdot p}\left(\frac{T}{273}\right)^{1.81}$$

R_D is the gas constant of water vapor, 462.10^{-6} Nm/(mg·K), and T is thermodynamic temperature in K. Therefore, the μ is independent on temperature and pressure as these are already expressed within the water vapor permeability. The measurement was provided by standard "dry cup" test with environment temperature of (23 ± 0.5)℃ and relative humidity 0/80% with utilization of climate chamber and silica gel under samples in the cup.

2.2.6. Moisture isotherm

The water vapor permeability of highly porous bio-based materials allows accumulation of moisture via adsorption from ambient air. The ambient air humidity causes monolayer water–vapor molecules adsorption on the surface of internal voids (pores) in monolayer adsorption continuing into multilayer until capillary condensation takes place (humidity > 90%). The moisture storage function for each material was obtained by measurements sorption and desorption curve according to EN ISO 12571. The initial conditions for sorption isotherm were represented by dry material and for desorption isotherm material with equilibrium moisture content under 23 °C and 98% humidity environment.

For determination of sorption and desorption isotherm moistures, 0%, 33%, 43%, 53%, 75%, 85%, and 98% of relative humidity were selected.

The sorption and desorption isotherms were expressed by moisture content mass by mass u [kg/kg] calculated from:

$$u = \frac{m - m_0}{m_0}$$

where m is the mass of test specimen and m_0 is the mass of dried specimen (EN ISO 12571 [41]).

Table 2
Average thicknesses, apparent density, porosity (with standard deviations) and number of specimen subjected to measurement.

Material	Number of specimens	Average thickness of specimen d [mm]	Apparent density ρ_v [kg/m^3]	Porosity [% m^3/m^3]
PE1	3	73.2 ± 3.5	64.2 ± 3.5	95.6 ± 0.1
PE2	3	38.3 ± 0.1	131.0 ± 1.2	90.9 ± 0.1
PS1	3	53.5 ± 2.9	66.4 ± 3.7	95.5 ± 0.1
PS2	3	32.0 ± 1.6	73.7 ± 4.9	95.0 ± 0.1
MO	3	38.2 ± 0.1	89.9 ± 2.0	93.6 ± 0.1
WO	3	38.1 ± 0.1	80.5 ± 0.3	94.5 ± 0.2
PW	5	100.0 ± 0.2	40.8 ± 0.6	97.6 ± 0.1
FE	5	38.3 ± 0.1	54.9 ± 0.4	95.8 ± 0.1

3. Results

3.1. Density and porosity of bio-based insulators

The densities ρ_v [kg/m^3] of studied materials were greater than light foam-based insulation materials, such as EPS or PUR foam. The measured densities were in the range of 40.8–131.0 kg/m^3, which corresponds to medium- or high-density level of glass and rock wool [45]. The least porous loose peat-based (PE2) insulation had the highest density (131.0 kg/m^3) and pulp wool (PW) had the lowest density (40.8 kg/m^3) (Table 2). The densities of the studied materials increased almost linearly with decreasing porosity (Fig. 2). The rates of porosity and density varied from 0.7 for PE2 to 2.4 for PW.

3.2. Thermal conductivity in relation to varying temperature and humidity

The mean thermal conductivities of all studied materials achieved values between 0.033 and 0.044 W/(mÂ·K) at temperature 10 °C. The standard deviation of the measurements was in all cases < 0.001 W/(mÂ·K). The lowest thermal conductivity was observed for the feather-based material (FE), which in terms of building envelope design would lead to decreasing thickness by 33% of the insulation compared to wood shavings-based material (WO) to achieve the same thermal performance. The thermal conductivities increased with increasing temperature (Fig. 3). The WO had a greater increasing tendency of thermal conductivity compared with the other materials examined. On the other hand, the feather-based insulation (FE) had the lowest and almost linearly increasing thermal conductivity throughout the measured temperature scale.

The thermal conductivity of the insulation materials was measured over a range of temperatures (Fig. 3) and relative humidity values (Fig. 4).

Peat and peat/moss-based materials (PE1, PS1, and PS2) were the most sensitive in the humidity interval 0–20%, where the thermal conductivity increased by 30%, 16%, and 20%, respectively (Fig. 4). From relative humidity 20–70%, the thermal conductivity increasing slowed to 14%, 16%, and 17%, respectively. When the relative humidity exceeded 70–80%, the thermal conductivity increased dramatically in all examined insulation materials. The reason is the interconnection of water–vapor molecules between individual pores. The thermal conductivity of paper wool (PW) increased exponentially throughout the humidity range. The remaining insulation materials exhibited relatively flat thermal conductivity curves increasing from 0% to 80%. The feather-based material (FE) exhibited the flattest increasing curve of thermal conductivity up to relative humidity 90%.

The thermal conductivity of dry material measured at uniform temperature also depends on the density of each insulator. Most insulation materials achieved the best thermal insulation properties in low-to-medium density range (approximately 40–60 kg/m^3), such as mixtures of straw, hemp and cellulosic fibers [46]. Below this range, the density usually indicates large coarse pores in which convective and radiation heat transfer occurs, resulting in increased thermal conductivity. On the other hand, high density increases the number of heat bridges that increases heat transfer by heat conduction, hence increasing thermal conductivity [47]. The feather-based (FE) insulator achieved the lowest thermal conductivity from the measured materials, although its density was higher than the paper wool insulation (PW). On the other hand, the wood chip (WO) insulation had the highest thermal conductivity despite its intermediate density of the materials examined. Use of *Sphagnum* moss decreased the density of the material and

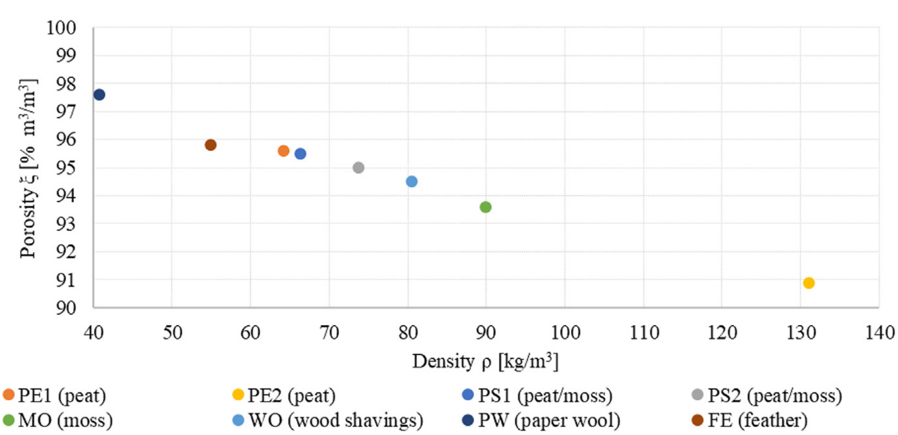

Fig. 2. Variation of porosity with relation to density of eight bio-based materials.

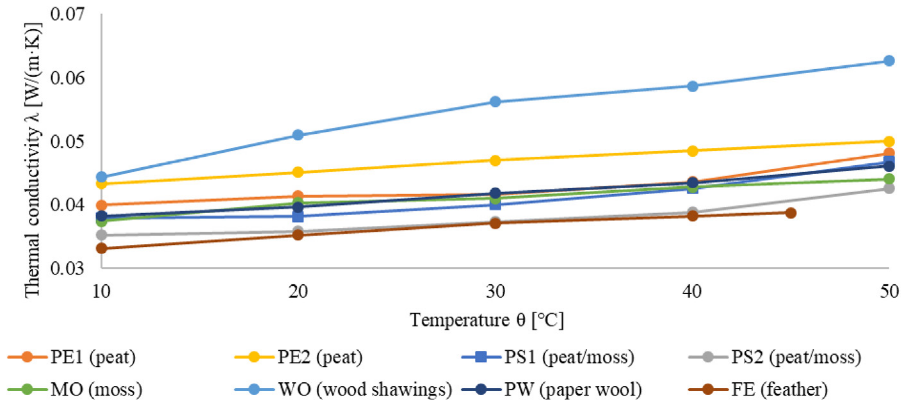

Fig. 3. Development of thermal conductivity depending on temperature variation of examined insulators.

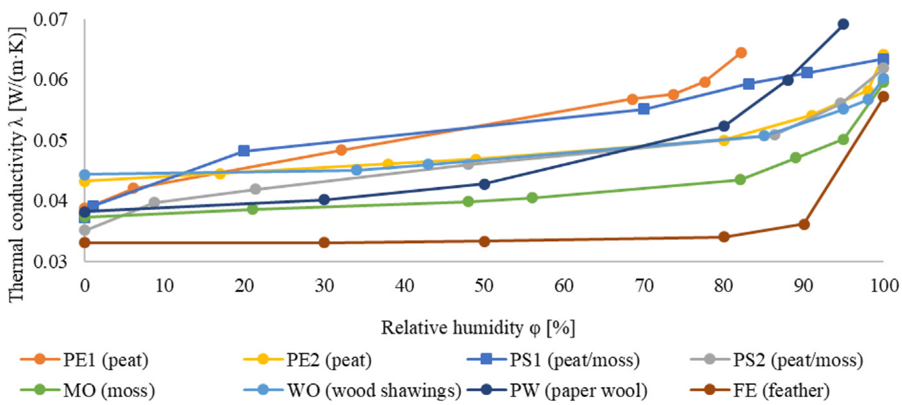

Fig. 4. Increasing of thermal conductivity according to relative humidity of the examined bio-based insulation materials.

increased its thermal resistance (PS2 and MO) at the tested densities. If it is assumed that the thermal conductivity increases in very low and high densities, the polynomial regression of thermal conductivity dependent on density of all measured insulators indicated high thermal resistance in the low-to-medium density range, which corresponds to the trend of most of the common thermal insulators [48] (Fig. 5). However, the structure of each thermal insulator is specific and the variation coefficient is significant.

3.3. Specific heat capacity of measured insulators

The mean specific heat capacity in dry state of each tested material varied from 1280 to 1490 J/(kg·K) (Fig. 6). The lowest heat capacity was obtained for wood shavings-based insulation (WO) and the highest for paper wool (PW). Peat/moss-based insulation materials (PE1 and PE2) had slightly higher heat capacity than the peat-based material, even though the heat capacity of the moss-based material (MO) was 8–11% less than material that contained peat. Therefore, peat had higher thermal storage capacity than moss. However, the heat capacity increased in the case of board insulation materials (PE1, PS1, and PS2), where the plastic binder affected the thermal properties of the materials studied. The loose insulation materials (PE2, MO, WO, and FE) had lower heat capacity than the board materials, with the exception of paper wool (PW), which had the highest heat capacity of all the materials examined. PW was also the most porous material with the lowest

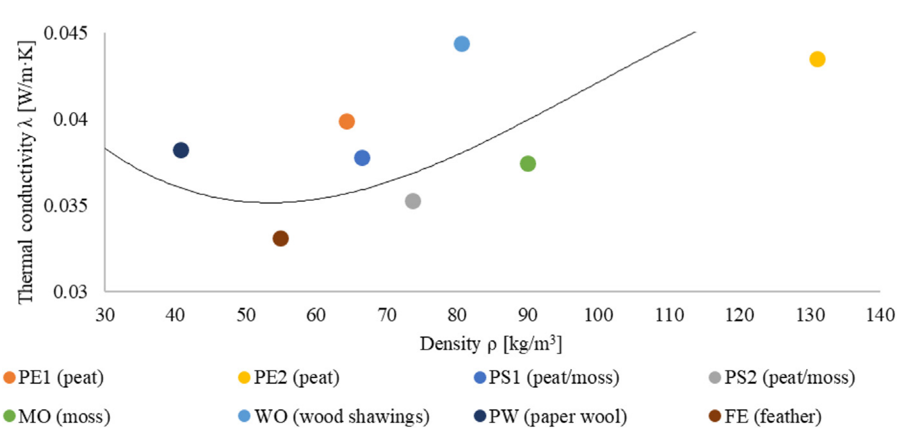

Fig. 5. Density-dependent thermal conductivity of the bio-based insulation materials examined and regression curve illustrating tendency of lowest thermal conductivity in density range of 40–60 kg/m^3.

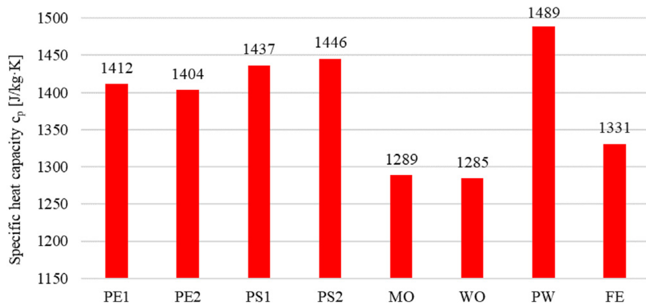

Fig. 6. Average specific heat capacity of examined insulation materials (average standard deviation of specific heat capacity for all samples is 11.3 J/(kg·K)).

density, which leads to the assumption that the raw paper wool material would have a heat capacity comparable with EPS [49].

3.4. Water vapour diffusion resistance

All the insulation materials examined were highly permeable for water vapor. The stabilization of diffusion flow during "dry cup" test in time was nearly linear for all tested materials (e.g. paper wool insulation (PW) Fig. 7). The water vapor diffusion resistance factor μ [-] of the tested materials was in the range of 2.3–3.9 (Table 3), which corresponds to wool insulation materials such as mineral wool [50], rock wool, glass wool, and wood fiberboard [45]. The diffusion resistance factor had a tendency to increase with increasing density of the material except for the peat-based insulations, which allowed the highest permeability regardless of the "high" density of the material.

3.5. Moisture isotherm of bio-based hygroscopic materials

All analyzed materials had the characteristic S-L shape (i.e., "Langmuir" type) of moisture isotherm (Fig. 8) [51]. The materials had high moisture storage capacity (>30% at 97% relative humidity), except peat and moss mix (PS1) and wood shavings (WO) (25% and 27% moisture content, respectively). For instance, the water content of wood fiber insulation at 97% relative humidity is approximately 20% [52,53] and the sorption of wood waste thermal insulation could be lower than 16% at 93% relative humidity [54]. The feather-based insulation exhibited a moisture content > 40% at 97% relative humidity, which was caused by a steep climb in humidity from 85 to 95%. The moisture storage isotherms show the hygroscopic nature of the studied materials. The materials overall showed low hysteresis as the ratio of average sorption and desorption (S/D). The standard deviation of the measurements was in all cases < 0.01 kg/kg. The hystereses were comparable with those of other natural hygroscopic materials, such as wood and wool [53]. The smallest hysteresis throughout the humidity scale was observed for the feather-based (FE) and pulp-wool (PW) insulations. However, the hystereses of FE and PW changed with relative humidity, where the hysteresis of FE was almost constant across the humidity range whereas the hysteresis of PW was significantly larger at humidity 75–93%. The largest hysteresis was observed for moss-based (MO) insulation.

4. Discussion

4.1. Thermal properties of bio-based materials

On the basis of the performed measurements, the examined insulation materials had thermal properties that compare favorably with conventional insulations. Due to a high air content (that has low thermal conductivity), thermal insulation usually benefits from high porosity. However, an increasing amount of air increases the humidity inside the pores. Water and water vapor reduce the thermal resistance of a building material and thus increase thermal conductivity. The thermal properties of the tested materials showed low thermal permeance resulting in high thermal resistance, which is applicable in low-energy buildings. The thermal conductivity of conventional insulations usually varies between 0.030 and 0.040 W/(m·K) [45]. The mean achieved values in this study varied between 0.033 and 0.044 W/(mÂ·K). As was also observed in the present study, it is generally expected that thermal conductivity decreases almost linearly with lower temperatures [55]. The thermal conductivity of materials based on peat (PE1 and PE2), *Sphagnum* moss (MO), mix of peat and *Sphagnum* moss (PS1 and PS2), wood shavings (WO), and recycled paper (PW) achieved slightly higher values than common mineral wool or EPS (range 4–30%). The lowest thermal conductivity from the

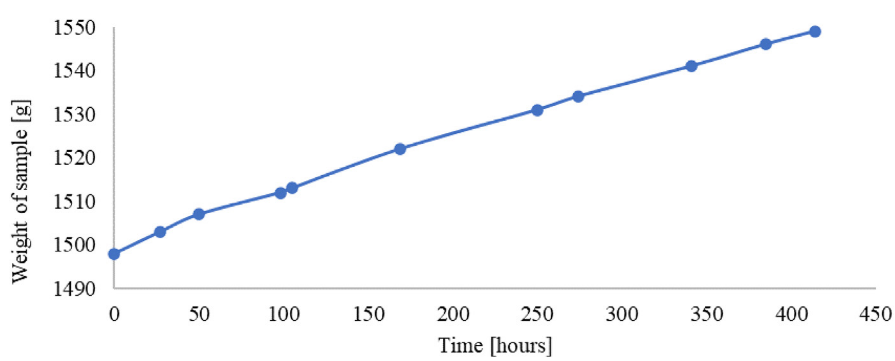

Fig. 7. Example of stabilization of diffusion flow during "dry cup" test of paper wool insulation (PW) sample to determine diffusion properties.

Table 3
Water vapor diffusion resistance factor and thicknesses with standard deviations of the insulation materials examined.

Parameter	PE1	PE2	PS1	PS2	MO	WO	PW	FE
Thickness of specimen d [mm]	63.8 ± 0.5	66.5 ± 0.5	49.0 ± 0.5	31.4 ± 0.2	69.0 ± 1.0	72.5 ± 0.5	93.0 ± 0.5	48.0 ± 1.0
Water vapor resistance factor μ [-]	2.3 ± 0.2	2.8 ± 0.1	2.8 ± 0.2	3.9 ± 0.5	3.3 ± 0.4	3.1 ± 0.7	2.6 ± 0.1	2.9 ± 0.2

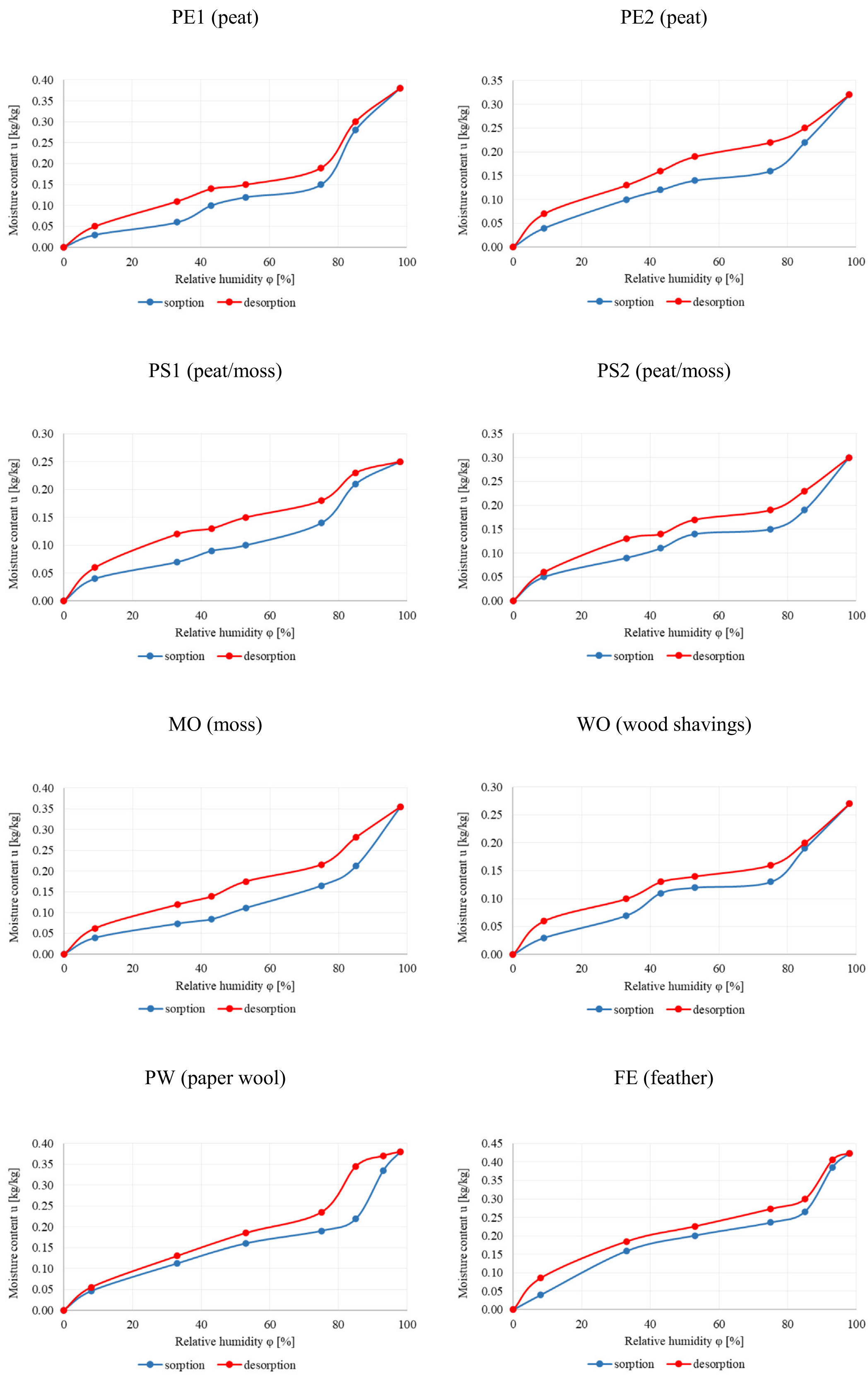

Fig. 8. Adsorption and desorption isotherms of examined materials.

tested materials was observed in the feather-based insulation (FE), which is comparable with high-quality glass wool [45].

It was assumed that the thermal conductivity of the tested materials would increase in density area from 60 kg/m^3, due to the reducing effect of heat transfer through air voids. However, the effect of heat conduction and convection inside the air voids decreases with increasing density. After achieving a critical number or size of pores, or both, the heat transfer through air voids is negligible compared with heat conduction through solid particles, and the relation of thermal conductivity and density turns back [56]. The thermal conductivity as a function of density of the studied materials does not show a clear influence on porosity. The feather-based (FE) material showed higher thermal resistance than the wood shavings-based (WO) material, although FE had higher density and porosity. The same effect is in comparison of peat and moss mix (PS2) with peat (PE1), peat and moss mix (PS1), recycled paper (PW), and (peat) PE2 with wood shavings (WO). The specific heat capacity of the tested bio-based materials is comparable for instance with EPS, but was almost two-fold higher than that of most of the wool-based insulation materials [45,50].

4.2. Hygrothermal properties of bio-based materials

The bio-based materials are generally characterized by low density and high porosity compared with other conventional building materials, such as wood-fiber boards (180 kg/m^3) [45] or insulators based on aerated autoclaved concrete (125 kg/m^3) or hard parts of hydrophilic thermal insulation (170 kg/m^3) [50]. Hence, the hygrothermal properties of the material depend on the humidity inside the air voids. The feather-based insulation (FE) material exhibited the lowest ratio of porosity and density. In the case of bast fiber insulations, the reason for low ratio of porosity and density has been suggested to be the low bulk density of the fiber conglomerates [8]. The structure of feather pieces could probably lead to somewhat similar air-containing conglomerates.

The low water vapor resistance factors (μ = 2.3–3.9) indicate sufficient permeability, which increases moisture penetration through the materials. The water vapor resistance factors are comparable with conventional wool-based insulation, such as glass wool (μ = 2.4), wood wool (μ = 3.6) [57], and thermal insulations based on natural fibers (μ = 2.1–4.0) [58]. Therefore, in the case of high humidity inside the materials, the permeability allows quick drying in a low-humidity environment. However, the hygrothermal performance of all insulation material significantly depends on assembly of building components and boundary conditions. The hygroscopic nature of the insulators, together with a well-designed indoor climate-control system, can improve energy efficiency of a building by up to 5% for heating and up to 30% for cooling [59].

4.3. Applicability and sensitivity of bio-based materials

Because bio-based insulation materials are derived primarily from organic matter, they may be more susceptible to microbial (e.g. microfungi, bacteria) growth than inorganic insulations. Hence, it is important to design a structural assembly that provides suitable hygrothermal conditions to avoid excessive humidity and thus prevent creation of a favorable environment for microbial growth [8]. Microbial growth may lead to degradation of building material and negatively influence indoor climate especially in cold outdoor climates, where heat and moisture transfer are directed mostly from the indoors outwards [60].

In this study, hygrothermal properties of the materials were examined without fire retardants to assess the basic potential of these materials as insulators. However, in practice fire performance is an important feature of thermal insulators. Cellulosic insulators are not fire resistant due to their chemical composition [8] and contain approximately 20% additives for fire retardancy [9,61,62]. The fire performance of the materials examined should be examined in future studies.

The composition of the investigated thermal insulators allows production of building elements applicable as insulation boards, loose material, or both in new buildings and in retrofitting. The materials provide high thermal resistance and water vapor permeability. All tested materials can be used in both vertical and horizontal building elements, such as building shells, attics, upper floors, and intermediate floors.

5. Conclusion

Sustainable buildings maximize their energy performance with minimum environmental impacts throughout the entire lifecycle. Bio-based insulation materials help decrease the environmental impacts of buildings by their low embodied energy. The present study assessed the hygrothermal properties of eight bio-based thermal insulation materials and their potential in new buildings, retrofits, or both. The output data provided important parameters for hygrothermal numerical models that allow for analyses of building hygrothermal performance and risk assessment of moisture accumulation inside building elements.

The measured hygrothermal properties of bio-based materials were comparable with widely used convection insulators. The thermal conductivity of the materials examined was between 0.033 and 0.044 W/(mÂ·K) at 10℃ and increased slightly with temperature to between 0.039 and 0.063 W/(mÂ·K) at 50℃. The bio-based insulators had the highest thermal resistance in the low-to-medium density range.

The water vapor diffusion resistance factor was in the range of 2.3–3.9, which indicates high permeability of the materials. The moisture storage isotherms revealed the hygroscopic nature of the materials with overall low hysteresis.

The material properties measured in this study provide suitable parameters applicable in low-energy buildings in accordance with current demands. Application of organic particles inside building components requires high-quality construction work to protect the materials from excessive humidity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the work reported in this article.

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