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To cite this article: F Pittau *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1078** 012069

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# Hygrothermal characterization of bio-based thermal insulation made of fibres from invasive alien lake plants bounded with mycelium

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**Abstract.** The European program 'Renovation Wave' aims to fasten the energy retrofit of the building stock by increasing by a factor 4 the current renovation rate. Mycelium-based materials gained momentum as insulation solutions in recent years due to their 100% biological composition. However, their durability issues, particularly the risk of fast decay due to high moisture content, need to be investigated to promote a safe use in construction. Two biocomposites were set up at a lab scale, a combination of hemp shives and mycelium and a novel mixture based on the combination of mycelium binder and fibres from a lake plant, *Lagarosiphon major*, an alien invasive species locally available in many EU internal waters. Samples with different dimensions were used to characterize through experimental tests the thermal conductivity, water absorption (capillarity) and vapor permeability. The results show that these mycelium-based composites present both hydric and thermal properties similar to other bio-based material used in construction. The capillarity tests highlighted that hemp composites absorb more water than lake plant ones. The thermal conductivity is similar for both biocomposites, i.e., around 0.05 W/m.K, while the moisture buffer position both analysed biocomposites in "WS 3" according to the German classification DIN 18947 for water regulators.

**Keywords:** bio-based insulation, mycelium, hygrothermal test

## 1. Introduction

Current research in the building sector underlines the need for energy-efficient designs and materials to reduce the environmental and economic impact of buildings [1], [2]. The European program 'Renovation Wave' aims to fasten the energy retrofit of the building stock by increasing by a factor 4 the current renovation rate [3] and the new Energy Performance of Buildings Directive (EPBD) requires for lower energy consumption solutions [4]. Consequently, a large demand for thermal insulation is expected in the next years, and the market should be ready to provide valid low-carbon solutions able to meet the demand for materials. In this context, biobased materials are interesting solutions due to: i) a fast regeneration in the biosphere [5]; ii) local availability [6], iii) clean process for manufacturing and waste treatment at the end-of-life [7]–[9]; iv) natural ability to store carbon in the biomass [10]; and v)



hygroscopic capacity [11]. The latter property gained momentum in the past years because of the passive control of humidity level [12], [13] while reducing the operational energy consumption of buildings [14], [15]. As a matter of fact, biobased materials are hygroscopic and usually exhibit good moisture-buffering capacities [16], meaning that they can absorb and release water from the air if exposed to different moisture loads and control the indoor air quality. In a circular economy perspective, they can be manufactured from agricultural, woody and aquatic biological waste [17] by promoting a not extractive material production strategies. In addition, there are other examples in literature that use the cutting-edge technology based on mycelium, the vegetative part of mushrooms, applied as a biological tool for naturally bind industrial and biological wastes [18], [19]. The mycelium, as it grows and branches out in space in search of food, is able to digest lingo-cellulosic biomass forming very light, natural composites as well as fire resistant [20]. Nowadays, there are examples in the literature that make use of this living being to assemble insulators or for interior applications, paving the way towards a wider use of biotechnology also in the world of construction [21], [22]. Moreover, mycelium binder permits to avoid the use of synthetic or mineral binder, which can emit pollutant and affect the indoor air quality (IAQ). Indeed, construction materials can be an important source of indoor pollutants, which combined to a poor ventilation, can have an impact on the IAQ and, consequently, on the health of the occupant [23]. Many existing products have already moved toward non harmful binders and additives to human health, namely sodium carbonate, silicate and clay [24], [25]. In the case of biobased and mycelium, the mold growth sensitivity needs also to be investigated as it can also affect the IAQ. Nevertheless, if the thermal conductivity has already been tested in scientific researches [18], [21], [26], mycelium-biobased materials' durability issues are not already systematically analyzed yet, in particular the risk of fast decay due to high moisture content that can prevent a safe use in construction [27]. Therefore, the aim of the current study is to measure in the laboratory the basic thermal conductivity and hygric properties, such as vapor permeability sorption isotherm, moisture buffering value (MBV) and capillarity, to provide necessary data for numerical hygrothermal simulations for durability predictions. Here, invasive lake plants, *Lagarosiphon major*, from the Endine Lake in the Lombardy Region in Italy and hemp shives were selected as case studies [28]. The first because every years the local authorities need to clean its water bodies from these invasive plants that are locally available in the main lakes in EU and listed in the EU banned list of invasive alien species. Therefore, by promoting their application as a novel mycelium-based materials one can create virtuous local circular economies while providing the necessary materials for insulating the building stock. The second, i.e., hemp shives, was chosen because in the hemp shives are ones of the most commonly used mycelium substrates [18], [29]–[31], ergo the obtained results for the thermal conductivity can be compared to the data already existing.

## 2. Materials and methods

### 2.1. Sample Compositions and Material Properties

In this research two biocomposites were analysed, one using lake plants as lignocellulosic substrate (Lake-Myc) and the other hemp shives (Hemp-Myc) to obtain mycelium-biobased composites as architectural insulation materials. The lake plants were collected onsite in early fall season, whereas the hemp shives were provided from the Italian company Tecnocanapa by Senini [32] with a fibre length of 0.25 mm. The production process of the mycelium-based samples followed the protocol proposed by Carcassi et al [33] for both substrates here used. In particular, the two substrates were first soaked in water for 24 h to be hydrated and dried for 7 h. In a second moment, they were homogenized in terms of length with a kitchen blender for a duration of 20 seconds and sterilized in a high-pressure autoclave up to a temperature of 121 °C and at pressure of 100 kPa for a duration of 20 min. Then, it was possible to proceed with the mycelium inoculation by dispersing 15 wt.% of fungal biomass into the plastic bags containing the sterilized substrates. A commercial rye spawn ready-mix with *Pleurotus ostreatus* spores was chosen and the inoculated substrates were stored in a controlled dark environment with a constant temperature of 25 °C and 90% relative humidity for overall 18 days. During the first 6 days, the mixtures

were put in plastic bags; secondly, they were placed in the mould for an additional 6 days to provide the desired shape to the material; lastly, the material was removed from the mould for the last 6 days to solidify the outer skin. To shape the samples, a 3D printed PLA moulds were selected. The samples were heat-treated in an electric oven at 70 °C for 12 hours until the mass stabilized and to stop the growing process and dehydrate the composite. For the thermal conductivity and MBV tests the same rectangular parallelepiped samples were used. In the case of capillarity other rectangular parallelepiped samples were produced, while for the vapor permeability cylindrical samples were necessary. Once the sample fabrication process was concluded, they were all weighted and measured in dry conditions (see Table 1). In total five samples were prepared for the lake plant typology and 9 for the hemp one. All the measurements were made with a balance accurate to  $\pm 0.01$  g and a calibre.

**Table 1.** Lake plants samples properties and tests that were conducted (TC=thermal conductivity; MBV= moisture buffer value; C= capillarity; P= Vapor permeability sorption isotherm)

Sample	Test	Thickness [mm]	Diameter [mm]	Width [mm]	Depth [mm]	Mass [g]	Dry Density ( $\rho_{dry}$ ) [kg/m <sup>3</sup> ]
<b>Lake plants (Lake-Myc)</b>							
A <sub>L</sub>	TC, MBV	42.2	/	149.0	149.0	187.9	200.5
B <sub>L</sub>	TC, MBV	40.6	/	141.0	145.0	163.0	196.4
C <sub>L</sub>	TC, MBV	46.0	/	143.0	140.0	202.2	219.5
D <sub>L</sub>	C	100.0	/	40.0	40.1	40.0	249.4
E <sub>L</sub>	C	94.0	/	36.0	38.0	29.0	225.4
<b>Hemp shives (Hemp-Myc)</b>							
A <sub>H</sub>	TC, MBV	41.6	/	150	150	106.8	114.1
B <sub>H</sub>	TC, MBV	40.3	/	150	150	123.9	136.6
C <sub>H</sub>	TC, MBV	42.3	/	150	150	113.7	119.5
D <sub>H</sub>	C	103.1	/	42.4	41.6	21.8	119.8
E <sub>H</sub>	C	102.9	/	41.8	40.2	20.6	119.3
F <sub>H</sub>	C	102.6	/	40.2	41.9	19.9	115.6
G <sub>H</sub>	P	50.2	109.8	/	/	55.9	117.9
H <sub>H</sub>	P	49.6	107.9	/	/	56.9	125.7
I <sub>H</sub>	P	50.1	109.7	/	/	57.4	121.3

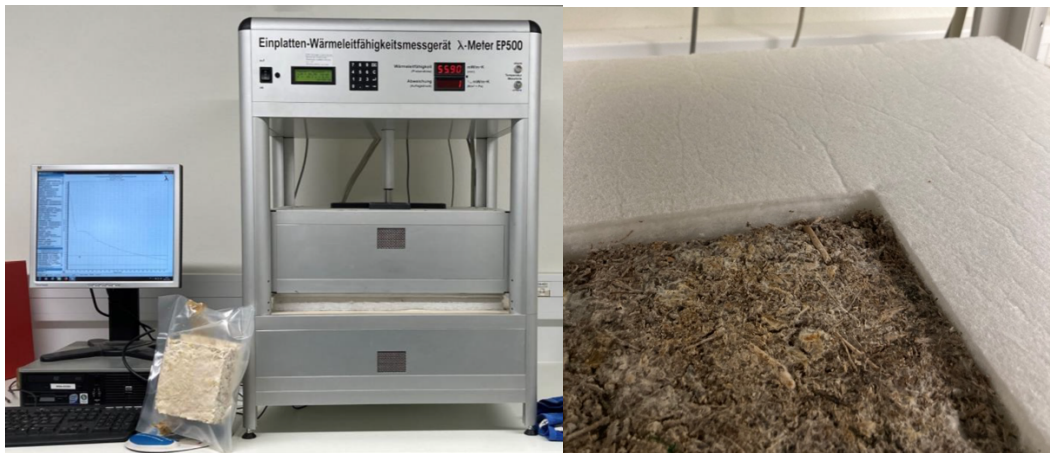
## 2.2. Thermal conductivity tests

Among the different types of equipments available for determining thermal conductivity, the guarded hot plate was chosen. Its functioning is based on the imposition of a constant heat flux  $\phi$ , obtained by the Joule effect, through the so-called hot plate with a surface area  $S$ , that is in contact in the opposite direction with another plate, the so-called cold plate. As the temperature difference between the two plates drives to a stationary heat flux, it is possible to obtain the thermal conductivity of the material according to the following Equation (1):

$$\lambda = \frac{\phi \cdot e}{S \cdot \Delta T} \quad (1)$$

where  $\lambda$  is the thermal conductivity of the sample expressed in W/m.K;  $\phi$  the heat flux (W);  $e$  the sample thickness (m);  $S$  the surface area (m<sup>2</sup>);  $\Delta T$  the temperature gradient (K).

The flow is assumed to be unidirectional in the direction normal to the plates. To limit the edge effects due to the finite dimension of the sample, an insulation material is used to surround the sample. To obtain reliable results, the contact between the sample and the plates must be assure (Figure 1-b). However, with such composites with heterogeneous surfaces, it was difficult to be in such required condition as in the case of most bio-based fibrous materials [34]. The duration of the rest is time consuming, as in most stationary methods, and it was around 2 hours per sample. Thermal conductivity values  $\lambda$  (W/m.K) were measured according to ISO 12664 standard. The Samples A,B,C of area 145 mm x 145 mm and thickness of around 43 mm were used during this tests. They were conditioned at relative humidity of 20% at 20 °C. Their thermal conductivities were then determined using the hot plate apparatus (l-Meter EP 500, Lambda- Messtechnik GmbH, Dresden) which measures the steady-state heat transfer through flat materials (Figure 1-a).



**Figure 1. a)** Thermal conductivity equipment. **b)** sample inserted in the insulation material to lower the edge effects

### 2.3. Hygric tests

**2.3.1. Vapor permeability.** The measurement of water vapor permeability factor was determined by the wet cup method described in ISO 12572, under isothermal conditions at 23 °C. The samples were sealed to the cups, where a saturated solution of potassium nitrate ( $\text{KNO}_3$ ) has been added in order to ensure a relative humidity inside of the cup of around  $94 \pm 1\%$ , the outside environment was set at 50% Relative Humidity (RH) by the climatic chamber (Binder MFK 720). The cups were regularly weighed until a steady state was reached, i.e. when the mass loss  $G$  ( $\text{kg}\cdot\text{s}^{-1}$ ) was constant.

**2.3.2. Moisture Buffering Value (MBV) and 'practical moisture content'  $w_{80}$ .** MBV represents the ability of the composite to regulate the relative humidity of a medium. To test the hygrothermal properties the German Industry norm DIN 18947 standard was followed, by using the same samples of the thermal conductivity ones. This norm was created especially for earth plasters but has also been used for different types of finishing materials. The results are expressed in  $\text{g}/\text{m}^2$  and a first classification is proposed (Table 2). This norm includes a description of a test method to characterize the water vapor adsorption capacity of the plaster under a 50% RH-80% RH step during 12 hours.

**Table 2.** German classification of moisture adsorption capacity of earth plasters [35].

Adsorption class	0.5 h	1h	3h	6h	12h
	( $\text{g}/\text{m}^2$ )	( $\text{g}/\text{m}^2$ )	( $\text{g}/\text{m}^2$ )	( $\text{g}/\text{m}^2$ )	( $\text{g}/\text{m}^2$ )
WS 1	$\geq 3 \cdot 5$	$\geq 7 \cdot 0$	$\geq 13 \cdot 5$	$\geq 20 \cdot 0$	$\geq 35 \cdot 0$

WS 2	≥5·0	≥10·0	≥20·0	≥30·0	≥47·5
WS 3	≥6·5	≥13·0	≥26·5	≥40·0	≥60·0

The experiment was performed using a CTS climatic test chamber (HPP1060, Memmert). The lateral and bottom surfaces of the tested samples were tightly sealed with aluminium foil on five sides, thus creating a barrier against the penetration of water vapor (Figure 2-b). Upper surface was left uncovered to expose them to moisture absorption and desorption. The samples were placed in a climate chamber and submitted to a change a relative humidity from 50% to 80% at a constant temperature of 23°C (Figure 2-a).



**Figure 2.** a) MBV equipment. b) sample used for both MBV and thermal conductivity tests.

Once the mass was stabilized (increasement of <1%) at 50% after 5 days, the RH was set at 80% and the mass was noted over a 12-h period. During the test, the temperature was kept constant at 23°C and the samples were weighed after 0.5, 1, 3, 6, 8, 12 hours, and then the samples were kept in this environment for other 7 days by noting the mass one time per day. Because several samples were weighed at the same time, the measurements were carried out outside the chamber, in less than 2 min. The short exposure time of the samples to different humidity conditions does not significantly interfere with the results. Therefore, the mass variation that corresponds to the water absorbed, is calculated as follow in Equation (2) to compare the mass increase after 12 hours with the German classification in Table 2:

$$\text{Adsorption Class} = \frac{\Delta m}{S} \quad (2)$$

where  $S$  ( $\text{m}^2$ ) is the surface of the sample in contact with air;  $\Delta m$  represents the mass variation during the adsorption phase expressed in g.

The practical moisture content  $w_{80}$  that corresponds to the equilibrium moisture at a relative humidity of 80% is a parameter needed in some hygrothermal software as COND or Wufi. Here it was obtained by stabilizing the samples at 80% RH in the climate chamber up to mass stabilization.

**2.3.3. Capillarity test.** For this test, the Standard ISO 15148 was followed. In case of capillarity determination, the bottom part of plastic flat container is covered in gravel and is filled with water at a depth of 5 mm above the gravel level (Figure 3-a). Before starting the capillary absorption process, all sealed samples are dried at 80 °C in a ventilated oven for dry mass determination. Their dry mass without sealing is also determined beforehand, but only for bulk density calculation, not for capillary absorption data analysis. The samples are wrapped with aluminium foil on the four lateral surfaces to ensure the sample is only exposed to the water at the bottom face (Figure 3-b). Moreover, a contour of 2 mm of the lateral surfaces were not wrapped to allow the contact with the water and then they immersed in the container for 9 days. The test procedure consists of recording, at defined time intervals, namely after 1,3,5,10,15,30 min and 1,4,8,24,72,96,168, 192, 216 hours, the mass increment by capillary suction of



a specimen with contact surface of samples with water, up to constant weight difference between two consecutive weightings less than 1%.



**Figure 3.** a) Capillarity test equipment. b) capillarity samples

### 3. Results

The mean values of thermal conductivity ( $\lambda$ ) obtained for the two biocomposites are reported in Table 3. Even if the density is higher in the Lake-Myc case, with a value of  $209 \text{ kg/m}^3$  and a  $\lambda$  of  $0.052 \text{ W/(m.K)}$ , the thermal conductivity is similar for both substrates obtaining a  $\lambda$  of  $0.053 \text{ W/(m.K)}$  from the Hemp-Myc composites. With respect to other biobased materials listed in Table 3, namely rice straw, wood fibres boards and hemp lime composites, the mycelium-based ones exhibit similar  $\lambda$  values to the wood fibres boards, and, in case of the Lake-Myc ones, also the density is comparable. Note the quite significant dispersion of the final dry densities in each mixture ( $>10\%$ ) reveals the difficulties encountered during the fabrication phase to produce a material with repeatable density, due to the presence of a living organism, the mycelium, as binding agent.

**Table 3.** Average thermal conductivity values of the two mycelium-based mixtures ( $\pm$  standard deviation). Hemp-Myc is the mixture with hemp shives; Lake-Myc is the mixture with lake plant.

Mixture	Hemp-Myc	Lake-Myc	Rice Straw [36]	Wood fibres boards [37]	Hemp lime [37]
Dry ( $\text{kg/m}^3$ )	$123 \pm 12$	$209 \pm 12$	80-100	212.2	286
$\lambda$ (W/mK)	$0.053 \pm 0.0048$	$0.052 \pm 0.0034$	0.039	0.054	0.064

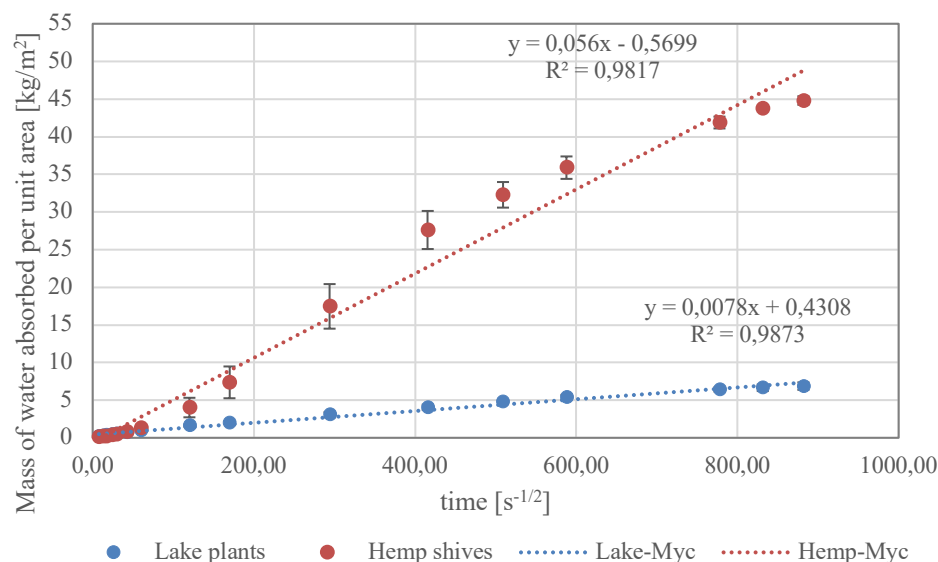
Average results and standard deviation for the water vapor resistance factor ( $\mu$ ) for the Hemp-Myc biocomposites are reported in Table 4, together with a comparison with other biobased insulation materials. Hemp-mycelium composites are characterized by a vapor diffusion resistance that are closer to the rice straw ones when compared with wood fibres boards and hemp lime composites. The water vapor resistance tests on lake plants biocomposites were unsuccessfully performed due to fast degradation of the samples under the chamber environmental conditions. Further investigation about mechanism understanding and data interpretation are needed in order to improve the samples quality and collect robust results for future tests.

**Table 4.** Water vapour resistance mean values for Hemp-Myc samples, measured by the method of wet cup, ( $\pm$  standard deviation).

Biobased materials	Hemp-Myc	Rice Straw [36]	Wood boards [37]	fibresHemp lime [37]
Water vapour diffusion resistance factor, $\mu$ (-)	$3.09 \pm 0.276$	3.25-5.47	4.2	2.5

Capillarity results are presented by mass of water absorbed per unit area ( $\text{kg}/\text{m}^2$ ) plotted against the square root of time ( $\text{s}^{-1/2}$ ) (Figure 4). Water absorption coefficient ( $A_w$ ) expresses the rate of capillarity action in certain time.  $A_w$  is mathematically defined as a tangent to capillary water content function, which was made explicit in Figure 4. For Hemp-Myc composites the  $A_w$  is equal to  $0.056 \text{ kg}/(\text{m}^2 \text{ s}^{1/2})$ , whereas Lake-Myc ones are characterized by lower values of  $A_w$ , namely  $0.0078 \text{ kg}/(\text{m}^2 \text{ s}^{1/2})$ .

The results indicate that the hemp ones absorbed more water with respect to the lake plants. This can suggest a biological structure of the fibres that are able to take in more water for the same surface section during an equivalent amount of tested period.



**Figure 4.** Mass of water absorbed per unit area over the square root of time ( $\text{s}^{-1/2}$ )

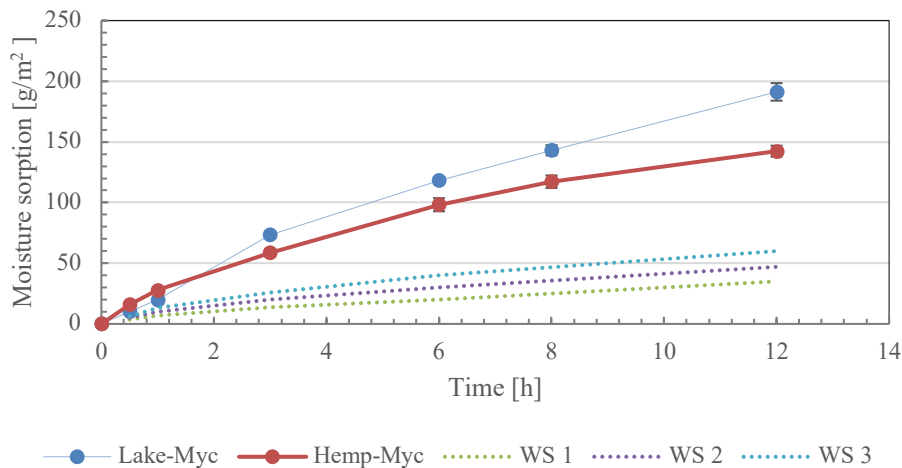
The moisture uptake through adsorption over time between 50% and 80% RH are shown in Figure 5 where the two mixtures, hemp and lake plants, are compared.

Moreover, the adsorption classes of earthen plaster according to the German norm is also reported in Figure 5 as dotted lines (WS1, WS2 and WS3).

The dotted lines in Figure 5 characterize the classification of moisture sorption properties with the lowest class as WS I and the highest class as WS III. The blue coloured curve describes the performance of Lake-Myc composites, the red curve presents the performance of Hemp-myc composites (lowest curve). The results presented in Figure 5 clearly show that the mycelium-based composites can be classified in the highest adsorption class with a values equal to  $201 \text{ g}/\text{m}^2$  for Lake-Myc calculated after 12 hours and  $183 \text{ g}/\text{m}^2$  for the Hemp-Myc ones, placing them as excellent environmental relative humidity regulators according to this classification. The results for the practical moisture content  $w_{80}$  are respectively  $0.12 \text{ kgwater}/\text{kgdrymat}$  for Lake-Myc and  $0.080 \text{ kgwater}/\text{kgdrymat}$  for Hemp-Myc



composites. These values highlight that, once stabilized at 80% of RH, lake plants absorbed more water with respect to hemp shives.



**Figure 5.** Adsorption data for 12 h cycles from 50% to 80% RH for Lake-Myc and Hemp-Myc composites according to DIN 18947.

Overall, the results of capillarity and moisture sorption suggest that the lake plant fibres are not so sensible to water, as opposed to hemp that appears to be have a more capillary fibre structure.

#### 4. Conclusions and discussion

The characterization tests carried out on the two mycelium-based composites (hemp and lake plants) allowed us to highlight the relationship with water. The capillarity tests highlighted that the Hemp-Myc mixture absorb more water with respect to the Lake-Myc. The thermal conductivity is similar for both biocomposites (around 0.05 W/m K). The moisture sorption revealed the hygroscopic nature of all composites. The MBV values position both analysed mixtures in “WS 3” water regulators according to the German classification [35] and shows the good potentials as environmental relative humidity regulators according to the DIN 18947. In general, these composites present interesting hydric and thermal properties. In comparison to other bio-based materials, mycelium-based composites have similar properties. They have the capacity to naturally regulate the humidity of the interior air by absorbing and desorbing water vapor, which may reduce need of HVAC, while assuring a thermal conductivity that is in line with the biobased materials [36], [37]. However, the moisture-buffering phenomenon is not limited to the materials scale and a definition of the moisture buffer value should be analysed at a wall scale in future studies and, the results here presented can serve as input data for numerical simulations with different wall archetypes. Moreover, moisture is known to promote the growth of microorganisms, discomfort, and also the degradation of the thermal stability and performance of biobased materials. Further assessments are needed to test the fungal evolution, water immersion, and fire test of these novel mycelium-based composites. In addition, surface treatments based can be analysed in order to create microbial degradation resistance and make these materials usable in practice in the building sector [38].

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