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Determination of hygrothermal parameters of experimental and commercial bio-based insulation materials

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HIGHLIGHTS

- The hygrothermal properties of six bio-based materials is experimentally analysed.
- The materials show remarkable differences in their hygrothermal performance.
- The results are compared to numerical simulations, obtaining a good agreement.
- Different materials may have different impacts on the overall building performance.

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ABSTRACT

The development and application of bio-based insulation materials can contribute to the minimization of the environmental impacts of buildings through reduction of embodied and in-use energy demand, in addition to many other major impacts such as resource depletion and waste generation. The hygrothermal performance of natural building materials has direct and indirect impacts on moderating indoor environmental conditions and can contribute to energy savings provided that such aspects are taken into account during the design and construction phases. This requires in-depth knowledge of the thermal and hygroscopic properties of the materials and their dependence on the moisture content. In this paper, the hygrothermal properties of six insulation materials is determined; four are commercially available materials while the other two are experimental materials based on crop by-products and natural binders. The influence of relative humidity on such properties is analysed. Moreover, the experimental Moisture Buffer Values are obtained for the six insulations, according to the protocol of the standard ISO 24353. Finally, a mass and heat coupled model is numerically solved to simulate this protocol for two of the materials, obtaining a good agreement with the experimental results.

1. Introduction

The building sector is moving towards new approaches of energy efficient design, which includes not only the decrease of the thermal transmittance of the building envelope but also the improvement and use of natural and locally available building materials. In this regard, interest in bio-based insulation materials is increasing because of the generally lower environmental impact of these materials compared to inorganic or petroleum based insulation materials [1]. Their low embodied energy, their biodegradability and their nontoxic nature are some of their environmental benefits [2].

In terms of their hygrothermal performance, probably the most relevant property of bio-based insulation materials is their high hygroscopicity. This means that such materials have the capacity to accumulate or release moisture in their internal porous structure by adsorption or desorption from the environment [3]. The amount of moisture accumulated is material specific and dependent on the relative humidity and the temperature of the environment. Thus, hygroscopic materials can be regarded as dynamic multi-phase systems (solid, the material matrix; liquid, the water adsorbed to the surface of the material; and gas, the air and water vapour within the pores of the material).

The above mentioned characteristic is relevant because all the basic thermal and hygric properties of hygroscopic materials depend on the moisture content [4]. Collet and Pretot [5] found a rate variation of thermal conductivity with moisture content about 0.0022 W/mK for each 1% of change in RH for hemp lime of

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between 0.090 and 0.160 W/mK, with little differences due to density and fibre/binder ratio. Other authors reported the variation of thermal conductivity with temperature to be from one to two orders of magnitude lower [6,7]. Thermal diffusivity is reported to be sensitive to moisture content as well. Carmeliet et al. [8] reported a reduction of 5–13% when the moisture content was doubled for brick and calcium silicate respectively. Jerman et al. [9] reported a rate variation of water vapour permeability of 0.13 10^{-6} m^2/s for each 1% of change in RH for an aerated concrete with a water vapour permeability (dry cup) of $2.17 \cdot 10^{-6}$ m^2/s. Finally, heat capacity significantly increases with moisture content due to the high specific heat capacity of water [4].

A certain amount of energy is associated with the adsorption process and the phase change of adsorbed moisture which also has implications for the thermal performance of the material. Therefore, it is clear that hygroscopicity has a direct influence on the energy performance of buildings. The extent and orientation (against or in favour of building energy efficiency) of such influence depends on each specific case and how this phenomenon is taken into account during the design and construction phases.

The understanding of the combined mechanisms of heat and mass transport in porous media is essential in the quantification of the thermal building performance. Different models have been proposed to describe the dynamic evolution of hygroscopic materials under variable environmental conditions of relative humidity and/or temperature [10–13]. Although there are some differences between the various models, all of them are based on the conservation of mass and energy. In their corresponding equations, there are some magnitudes (thermal conductivity, density, specific heat, water vapour permeability) that depend on relative humidity, and therefore a complete knowledge of the material hygrothermal properties is needed in order to numerically solve the equations.

The capacity of adsorbing and desorbing moisture enables hygroscopic materials to act as a moisture buffer, moderating extremes of humidity in an indoor environment [14–16]. This has positive effects on indoor air quality and might enable a reduction of the ventilation rate and thus, of heat loses. The moisture buffer performance of a room is the ability of the materials within the room to moderate variations in the relative humidity. The NORDTEST Project [17,18] and the Japanese Industrial Standard JIS A 1470-1 (2002) introduced a useful index to quantify the moisture buffer capacity of a material in conditions of surrounding humidity variation. The Moisture Buffer Value (MBV) indicates the amount of water vapour that is transported in or out of a material, when the sample is exposed to cyclic step-changes in relative humidity between high and low values for determined periods of time. A related index is included in the international standard ISO 24353. It is a material/environment characterisation, and thus is affected by air speed and depends on the air surface resistance [17,19]. The MBV is normalized per % of relative humidity variation, and its units are kg/(m^2%RH).

In the present work the hygrothermal properties of six insulation materials (four commercially available and two experimental materials) are compared. The dependence of thermal conductivity, thermal diffusivity and water vapour permeability with relative humidity is experimentally determined. Experimental Moisture Buffer Values are obtained for the six insulations, and these values are compared with numerical results obtained from a dynamical model.

2. Dynamical model

The heat and mass transport in porous media can be modelled, under certain assumptions, by a set of one-dimensional coupled equations [14] which account for conservation of mass (adsorbed and gas phases) and energy:

$$\rho_l \frac{\partial \varepsilon_l}{\partial t} + \dot{m} = 0 \tag{1}$$

$$\frac{\partial(\rho_v \varepsilon_g)}{\partial t} - \dot{m} = \frac{\partial}{\partial x}\left(D_v \frac{\partial \rho_v}{\partial x}\right) \tag{2}$$

$$\rho C_p \frac{\partial T}{\partial t} + \dot{m} h_{ad} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) \tag{3}$$

where t is the time and x the spatial position along the width of the sample. In these equations $\varepsilon_l(x,t)$ and $\varepsilon_g(x,t)$ are the volume fractions of liquid and gas phases respectively, $\rho_v(x,t)$ is the vapour water density and T(x,t) is the temperature. Volume fractions are constrained by the relationship $\varepsilon_l(x,t)+\varepsilon_g(x,t)+\varepsilon_s = 1$, where ε_s is the volume fraction of the solid walls of the material. ρ_l is the liquid water density and h_{ad} is the latent heat of sorption. From each pair of local and instantaneous values of vapour density and temperature, the relative humidity ϕ can be evaluated by using thermodynamic relationships. ϕ = Pv/Psat, where Pv is the vapour pressure and Psat the saturation vapour pressure at temperature T. The vapour diffusion coefficient, D_v, is evaluated from the water vapour permeability δ as $D_v = \delta$ Rv T, with Rv being the gas constant for water vapour. The magnitudes λ(thermal conductivity), δ (water vapour permeability) and ρC_p (product of density by heat capacity of the sample) depend on the relative humidity, so they need to be re-evaluated each time step. $\dot{m}(x,t)$ is the phase change rate per unit volume and can be evaluated from the moisture content, u, as:

$$\dot{m} = -\rho_0 \frac{\partial u}{\partial t} \tag{4}$$

where ρ_0 is the dry density of the material. Moisture content u depends on relative humidity according to its corresponding sorption isotherm curve. In conclusion, in order to use Eqs. (1)–(4), there are four magnitudes which dependence with relative humidity should be known: u, λ, D_v, and ρC_p. In the next section, these dependences have been experimentally obtained for six insulation materials.

3. Materials and methods

3.1. Materials and samples

Samples of six different bio-based insulation materials were used. Four of them, namely, hemp lime (HL), hemp fibre (HF), wood wool (WW) and wood fibre (WF), are commercially available thermal insulations, while the barley straw-starch (BS) and corn pith-alginate (CA) are experimental insulation materials. Formulations for the latter were optimized in previous work in order to obtain suitable composites [20]. The basic properties and composition of the tested materials are listed in Table 1.

3.2. Thermal conductivity and diffusivity

With the aim to determine the influence of relative humidity on thermal conductivity and thermal diffusivity of the insulation materials, samples of 200 × 200 × 40 mm were prepared. They were conditioned at different relative humidities at 20 °C in sealed capsules containing saturated salt solutions for at least two weeks. Their thermal conductivity and thermal diffusivity was then determined with the Quickline-30 Electronic Thermal Properties Analyser using a surface probe with a disk sensor. Such equipment is based on the analysis of the temperature response of the material to heat flow impulses induced by electrical heating using a resistor