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Influence of temperature on sorption process in hemp concrete

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HIGHLIGHTS

- Hemp concrete sorption isotherms are measured at two different temperatures.
- Both coupled hysteresis and temperature effects are investigated.
- Hysteresis and thermodynamic models are used.

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ABSTRACT

Hemp concrete is a bio-based material which is currently undergoing a growing development. Its hygrothermal behaviour highly depends on the evolution of the moisture content which has a significant influence on heat and moisture transfer. Hysteresis phenomenon and temperature effects on sorption process make difficult the prediction of the moisture content evolution. Hysteresis phenomenon determines the equilibrium moisture content during successive adsorption/desorption cycles. Temperature influences also the equilibrium moisture content: the warmer the temperature, the lower will be the equilibrium moisture content at the same relative humidity. These two phenomena are most often neglected for modelling the moisture content evolution in heat and moisture transfer models. This can cause significant discrepancies to predict the hygrothermal response of a material subjected to climatic variations.

This paper intents to contribute to the better knowledge of such sorption processes by providing new measurements and by analysing and comparing different theoretical approaches. Some adsorption and desorption main and intermediate scanning curves are measured at two different temperatures. Models taking into account these phenomena are presented. The comparison between experimental and numerical results shows that the theoretical approaches investigated are promising.

1. Introduction

In a context of sustainable development, one of the concerns in the building construction sector is the choice of environmentally friendly and healthy materials. In the French climatic conditions, bio-based materials appear as a good solution to address energetic and environmental issues [1]. Different compositions and methods of manufacturing give to hemp concrete a variety of use: wall, floor and roof. For wall, hemp concrete can be precast, moulded in place or sprayed. Because of low mechanical properties [2], it is mainly used as a filling material supported on a timber frame.

Previous studies on hemp concrete showed its interesting hygrothermal properties as building materials: a low bulk density from 300 to 500 $kg\,m^{-3}$, a low thermal conductivity of about 0.1 $W\,m^{-1}\,K^{-1}$ and a high vapour permeability of 10^{-11} to 10^{-10} $kg\,m^{-1}\,s^{-1}\,Pa^{-1}$ [3–7]. Its porous, hygroscopic and permeable structure gives high moisture transfer and storage capacities. In [8,9], the high moisture buffer value of hemp concrete confirmed its excellent moisture buffer performance. In practice, the monitoring of an individual French dwelling-house made of 30 cm thick sprayed hemp concrete associated with a timber frame structure [10] and of an experimental hemp-lime building house in England [11] showed its ability to dampen variations of temperature and relative humidity.

Previous works showed the significant influence of moisture content on heat and moisture transfer and storage [7,12–15]. The derivation of the hygrothermal response to climatic variations of

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a bio-based material like hemp concrete needs thus a thorough knowledge of the moisture content evolution.

As observed for many hygroscopic materials, a significant hysteresis occurs in the hemp concrete sorption process [5,13]. For these materials, the equilibrium moisture content depends not only on relative humidity but also on moisture history.

For hemp concrete, the hysteretic phenomenon was experimentally and numerically studied at the reference temperature of 23 °C in [13]. In this work, the Huang hysteresis model [16] showed its suitability to numerically predict the hemp concrete hysteretic behaviour.

Numerical results in good agreement with experimental ones showed the relevance to consider the hysteresis phenomenon to simulate the transient hygric response of hemp concrete [13–15].

These results were obtained at ambient temperature (about 23 °C) but temperature variations can also affect the evolution of moisture content [17,18]. The latest experimental research highlights the influence of temperature on moisture content for cement-based materials and ordinary concrete [19–23]. Some experimental investigations were also performed on wood [24,25]. These studies were mainly focused on a high range of temperatures over 20 °C up to 80 °C for specific applications (durability, drying process...). Others dealt with organic-based products in a temperature range close to the one encountered in operative building applications between 0 °C and 40 °C [26–29]. In all studies, the warmer the temperature, the lower the equilibrium moisture content at the same relative humidity was.

In this framework, theoretical and numerical approaches are developed to predict the temperature's effect on moisture content. Three main theories try to explain the influence of temperature on sorption isotherms. The modification of the pore structure due to temperature is one explication. Determination of specific surface areas and mercury intrusion porosimetry tests on cement-based material were performed at different temperatures [30,31]. A temperature increase between ambient temperature and 90 °C or 100 °C results in a reduction of the specific surface area. The comparison of the pore size distributions shows the presence of pores with larger diameters at 80 °C than at 30 °C. A modification of the microstructure by an enlargement of pores can thus be attributed to a rise of temperature. This can explain the modification of the sorption isotherms shapes until a temperature of 60 °C [32]. Nevertheless, this approach is to be found insufficient to explain the decrease of moisture content at saturation observed in a large range of temperature (between 20 °C and 80 °C) for cement-based materials [21–23]. To overcome the limitations of the microstructure alteration with the increase of temperature, the modification of the water thermophysical properties with temperature was also investigated together with coarsening of the pore structure [33,34] or without [35]. Poyet suggested that the microstructure alteration and the water properties evolution had negligible effects and did not fully explain the results obtained for concrete [21]. He proposed a new approach based on the thermodynamic evolution of sorption mechanism [21]. He based his approach on the exothermic process of adsorption [36] and on the principle of Le Chatelier and the rule of Van't Hoff. According to these principles, increasing temperature promotes the reverse process of adsorption, namely desorption. This approach was validated on cement pastes and concretes [21,37].

Research on temperature effects, on hysteresis effects or on the coupling between temperature and hysteresis are rather scarce in literature. Rode et al. [38] provided some measurements for several building materials (cement paste, spruce, aerated concrete). For the three temperatures investigated (10 °C, 25 °C and 40 °C), no significant differences were observed for aerated concrete both in adsorption and desorption for a range of relative humidity between 10% and 80%. For very high relative humidities over 80% and very low below 10%, more differences are observed between each sorption isotherms. Furthermore, the results obtained by Rode et al. are in accordance with the hypothesis of Ishida [39] which assumes that an increase of temperature results in a reduction of the hysteresis loop.

This paper aims to provide some experimental measures to identify the influence of both temperature and hysteresis on the moisture content evolution in hemp concrete. The range of relative humidity between 20%RH and 85%RH chosen in this paper is supposed to be representative of the variations in France for a hemp concrete wall in typical configuration. Hysteresis phenomenon is modelled using the Huang hysteresis model. The theoretical approach (thermodynamic equilibrium move) used for concretes and cement-based materials is applied in the case of hemp concrete. The performance of the thermodynamic model is compared with experimental results collected on hemp concrete at two different temperatures. This approach is extended to model the influence of both hysteresis and temperature and the results are discussed.

2. Theory

2.1. Sorption isotherm modelling

Different approaches are to be found in literature to model the sorption isotherms. In this paper, two models are chosen and compared: the GAB model based on the physical sorption mechanism [40–44] and the Van Genuchten (VG) model based on the moisture transport [45].

The GAB equation is described by Eq. (1):

$$u_j(RH) = \frac{a_j b_j u_m RH}{(1-b_j RH)[1+(a_j-1)b_j RH]} = \frac{u_{sat} RH(1-b_j)[1+(a_j-1)b_j]}{(1-b_j RH)[1+(a_j-1)b_j RH]}\qquad j = ads\ or\ des \tag{1}$$

where u_{ads} [kg/kg] and u_{des} [kg/kg] represent the main adsorption and desorption functions, respectively, RH [%] the relative humidity. u_m [kg/kg] is the molecular moisture content, u_{sat} [kg/kg] is the saturated moisture content, a_j and b_j depend on the molar heat of adsorption and the molar latent heat of vaporisation. In practice, parameters are derived to fit experimental data.

The VG model was initially developed to predict the unsaturated hydraulic conductivity in soils and the equation of the model was then adapted for building materials by using relative humidity instead of capillary suction as state variable. It mathematically describes the main adsorption and desorption curves with a single relation given by Eq. (2):

$$u_j(RH) = u_{sat}\left[\left(1+\left|\alpha_j \frac{RT}{M_l g} ln(RH)\right|^{\eta_j}\right)^{-\left(1-\frac{1}{\eta_j}\right)}\right],\ j = ads\ or\ des \tag{2}$$

u_{sat} [kg/kg] is the saturated moisture content. R [8.314 J mol^{-1} K^{-1}] is the ideal gas constant, M_l [18 g mol^{-1}] the molar water mass, g [9.81 m^2 s^{-1}] the gravity acceleration and T [296.15 K] the reference temperature. Parameters α_j and η_j are calculated by fitting experimental data.

2.2. Hysteresis modelling

Fig. 1 provides a schematic view of a hysteresis loop for a desorption/adsorption cycle.

According to Huang's model, Eqs. (3) and (4) describe respectively the adsorption and desorption scanning curves after a series of alternating processes of desorption and adsorption:

$$u(RH, i) = u_r(i) + (u_s(i) - u_r(i))\frac{u_{ads}(RH)}{u_{sat}} \tag{3}$$