

Experimental characterization and numerical modelling of the hygrothermal behaviour of an aerated cellular concrete

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Abstract - The hygrothermal properties modelling of construction materials depending mainly at the 1st order on the moisture content evolution remains superficial in literature works especially for hygroscopic materials. Indeed, the complexity of sorption mechanisms (hysteresis and sorption thermodependency) is very often not considered. This research work is therefore dedicated, on one hand, to complete the experimental characterization data and to model the hygrothermal properties of an aerated cellular concrete. The physical, thermal and hygric properties are measured. On the other hand, the numerical hygrothermal response of the studied samples subjected to cyclic hygrothermal variations, defined according to the NORDTEST protocol and obtained from a transient moisture and heat transfer model, is discussed and compared to the experimental results.

Nomenclature

A_w liquid absorption coefficient, $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-0.5}$
 c specific heat, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
 D_w liquid transport coefficient, $\text{m}^2\cdot\text{s}^{-1}$
 g moisture flow, $\text{kg}^{-1}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$
 l_v latent heat of evaporation, $\text{J}\cdot\text{K}^{-1}$
 m weight, kg
 n open porosity, %
 u moisture content, $\text{kg}\cdot\text{kg}^{-1}$
 RH relative humidity, -
 T temperature, K

Greek symbols

δ_p vapour permeability, $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$
 λ thermal conductivity, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
 ρ bulk density, $\text{kg}\cdot\text{m}^{-3}$

Index and exponent

* equivalent
 0 dry state
 l liquid
 ref reference
 sat saturation
 v vapour
 w water

1. Introduction

In France and Europe, the building sector represents more than 40% of energy consumption and about 25% of CO₂ emissions [1, 2]. Zhang et al. highlights the potential of Aerated Cellular Concrete (ACC) as a sustainable alternative to traditional building materials due to its lightweight, structural performance, highly porous structure, and thermally insulating properties [3].

For ACC, like other hygroscopic materials, moisture content depends not only on relative humidity but also on moisture and temperature variations previously lived by the material.

Therefore, a special focus is given to the moisture content evaluation in this study. Indeed, moisture content is the most influent parameter which govern the hygrothermal response of a material subjected to hygrothermal variations [4]. The hysteresis phenomenon and the thermo-dependent sorption mechanism of ACC should be carefully evaluated in order to accurately predict its moisture content evolution. In this paper, the main hygrothermal properties experimentally characterized are presented. Sorption isotherms of ACC at 2 different temperatures are also experimentally presented. Different numerical models are also discussed and compared to the collected experimental data. The hysteretic effect is a phenomenon that results in the moisture content of a material being influenced not only by the current relative humidity, but also by its “moisture history”. Porous materials are particularly sensitive to this effect. In addition, the equilibrium moisture content of a material is strongly influenced by the temperature, with higher temperatures leading to lower equilibrium moisture content and lower temperatures leading to higher equilibrium moisture content. Despite the importance of these effects, they are frequently disregarded in heat and moisture transfer models, leading to significant discrepancies when predicting the hygrothermal response of a material subjected to climatic variations.

Furthermore, the NORDTEST project aims to fulfill a test method for measuring the moisture buffer performance of materials and establish reference measurements on representative materials [5]. The MBV experiments (MBV: Moisture Buffer Value) involve subjecting building materials to cyclic changes in relative humidity in a controlled environment and measuring the moisture uptake and release of the material.

The modelling of the ACC hygrothermal properties, especially the moisture content, are then implemented in a heat and moisture transfer model. Experimental and numerical results are compared in order to evaluate the effective response of ACC to the cyclic climatic variations suggested by the Nordtest protocol.

2. Materials

ACC is mainly composed of sand, cement and lime, but also of gypsum and expansion agents. The physical and hygrothermal properties of ACC are widely studied in literature. The macroscopic and microscopic views of the studied ACC are shown in Figure 1. Micro and macroscopic analysis of AAC reveals its high porosity, showcasing air voids' size, distribution, and connectivity. This insight is very useful for understanding moisture permeability and sorption mechanisms.

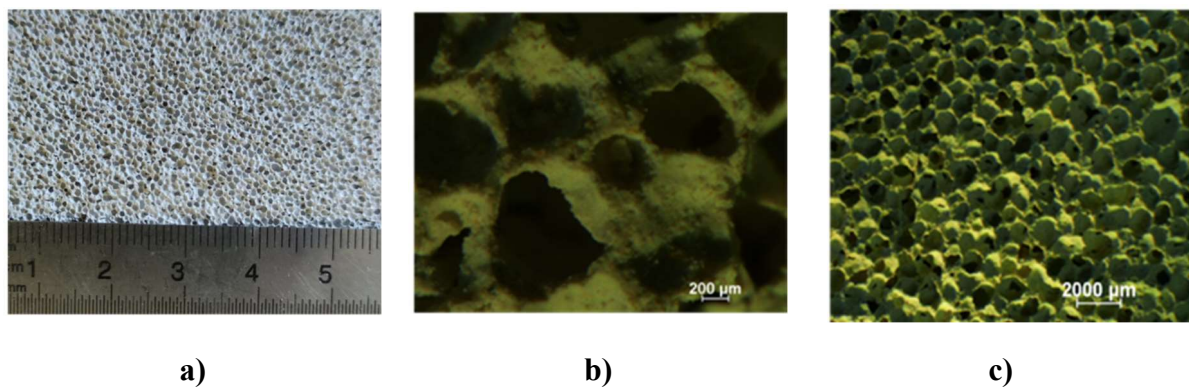


Figure 1: ACC macroscopic a) and microscopic views b) and c)

The dimensions of the samples used to determine the main hygrothermal properties are specified in the standards referenced later in this paper. 6 samples are tested for each property

characterization. The dimensions of the parallelepiped samples used to perform the MBV tests are according to the NORDTEST protocol [5]. One can note that the moisture penetration depth is theoretically evaluated to around 4.7 cm for ACC [6].

The number and sizes of the different samples 'dimensions (length×width×depth) series are respectively:

- S1: 0.1×0.1×0.1 m³ tested 3 times for 6 examples
- S2: 0.1×0.1×0.05 m³ tested 3 times for 6 examples
- S3: 0.12×0.12×0.1 m³ tested 1 time for 6 examples

3. Methods

3.1. Hygrothermal properties: Standard experimental characterization

3.1.1. Physical characterization

According to the NF EN ISO 12570 [7], all the samples are first dried to a constant weight m_0 in a ventilated oven at 105°C until steady state when the mass variation for 3 consecutive measurements during 24 hours is less than 0.1%.

The saturated moisture content u_{sat} [kg.kg⁻¹] is determined from Eq 1. where $m_{air,sat}$, the weight of the water saturated sample in air and m_0 are experimentally measured. To obtain $m_{air,sat}$, the air pressure in pores is gradually reduced and maintained at a value close to vacuum. Then, the samples are fully immersed and the saturated moisture content u_{sat} may be determined:

$$u_{sat} = \frac{m_{air,sat} - m_0}{m_0} \quad (1)$$

The open porosity n [-] is defined by the relation:

$$n = \frac{u_{sat}\rho_0}{\rho_w} \quad (2)$$

The dry bulk density of the parallelepiped samples is determined with a 520-g VWR LPW-503i balance (accuracy 10⁻³ g) and a calliper (accuracy 10⁻¹ mm).

3.1.2. Hygric characterization

The adsorption and desorption isotherms are determined according to the standard NF EN ISO 12571 [8]. The adsorption and desorption isotherms are determined at two temperatures, 10°C and 23°C, from the dry state for six relative humidities: 11, 22, 53, 69, 81 and 97%RH in a climatic chamber. The samples are periodically weighed until the difference between three consecutive measurements during 24 hours is less than 0.1%.

The mass moisture content u is determined from Eq. 3.

$$u = \frac{m - m_0}{m_0} \quad (3)$$

The vapour permeability δ_p (kg.m⁻¹.s⁻¹ Pa⁻¹) is measured as specified in standard NF EN ISO 12572 [9].

The liquid water absorption coefficient A_w [kg.m⁻².s^{-0.5}] is determined according to NF EN 15148 [10] from the evolution of the water mass in the sample in function of time. The evolution of the liquid transport coefficient D_w [m².s⁻¹] is defined by Eq. (4) [11].

$$D_w = 3.8 \left(\frac{A_w}{\rho_0 u_{sat}} \right)^2 1000 u_{sat}^{-1} \quad (4)$$

3.1.3. Thermal characterization

The thermal properties of ACC are determined respectively from the hot wire method for the thermal conductivity, from the hot plane method for the thermal effusivity and from hot ring method for the thermal diffusivity with a Neotim device. These properties have been determined at 6 different relative humidities: 11, 22, 53, 69, 81 and 97%RH and at saturation.

3.2. The MBV test

This section presents the Round Robin Test proposed to establish a test method for measuring the moisture buffer performance of building materials. The NORDTEST project aims to fulfill this need and establish reference measurements on representative materials, while ensuring testing laboratories can handle the method. The principle is based on the monitoring of the moisture samples' weight, sealed on all surfaces excepted one. As proposed by the NORDTEST protocol, the specimens are subjected to RH variations cycles during one week. Here, the RH setpoints are defined at 75% during 8h and 33%RH during 16h.

One limitation of the NORDTEST protocol is that the initial moisture content is undefined. In this study, the samples are dried until constant mass in order to impose a known initial moisture content close to 0%.

4. Theory

4.1. Moisture and heat transfer modelling

According to Künzel formalism [11], the driving potentials of the 1D hygrothermal model can be expressed in terms of two flow potentials: temperature T and relative humidity RH. The governing system of equations of moisture and heat transfer is given in Equations (5 and 6).

$$\rho_0 c^* \frac{\partial T}{\partial t} = \nabla[\lambda^* \nabla(T)] + \nabla \left[(l_v + c_v(T - T_{ref})) g_v \right] + \nabla [c_l(T - T_{ref}) g_l] \quad (5)$$

$$\frac{\partial w}{\partial t} = \nabla [\delta_p \nabla(RH p_{sat})] + \nabla [D_l^{RH} \nabla(RH)] \quad (6)$$

$D_l^{RH} = D_w \frac{\partial w}{\partial R} \Big|_T$ is the liquid diffusion coefficient under relative humidity gradient [$\text{kg}^{-1} \cdot \text{m}^1 \text{ s}^{-1}$].

The governing system of strongly coupled unsteady differential equations implemented in Matlab with a finite differences method was validated against the international benchmark HAMSTAD WP2 [12].

4.2. Moisture sorption modelling

4.2.1. The main sorption models

It exists many models in literature to describe the main sorption isotherms. In this paper, 2 models are used.

The GAB (Guggenheim - Anderson - De Boer) model based on the physical sorption mechanism is first selected.

The GAB equation written in its modified form [13, 14] is described by Eq. 7:

$$u = \frac{u_{sat}RH}{(1 - b_jRH)[1 + (a_j - 1)b_jRH]}(1 - b_j)[1 + (a_j - 1)b_j], j = ads \text{ or } des \quad (7)$$

a_j and b_j depend on molar heat of adsorption and molar latent heat of vaporization. In practice, the parameters a_j and b_j are derived to fit experimental data.

The Van Genuchten (VG) model is described by Eq. 8 [15].

$$u = u_{sat} \left(1 + \left| \alpha_j \frac{RT}{M_l g} \ln(RH) \right|^{\eta_j} \right)^{-\left(1 - \frac{1}{\eta_j}\right)}, j = ads \text{ or } des \quad (8)$$

The parameters α_j and η_j are derived to fit experimental data.

Especially, the main desorption parameters are determined by using a hysteresis model (described hereafter) to fit the experimental primary desorption curve 97-0%RH.

4.2.2. The hysteresis phenomenon modelling

An increase in ambient relative humidity during the adsorption phase leads to an increase in moisture content in the material, while in the desorption phase, less moisture is released than taken up during adsorption for the same relative humidity change. The equilibrium moisture content during adsorption and desorption is found to be different, a phenomenon known as hysteresis. This paper uses the Huang model [16], which has demonstrated effective performance for a variety of soils and construction materials, to simulate the hysteresis effect.

4.2.3. The thermodependency sorption mechanisms

The effect of the temperature on moisture content is based on the exothermic process of adsorption. According to the principle of Le Chatelier and the thermodynamical law of Van't Hoff, if the conditions of a system in equilibrium are modified, it reacts so as to oppose the changes until a new equilibrium. Thus, the exothermic nature of adsorption mechanism implies that an increase of temperature leads to a decrease of the number of adsorbed molecules and therefore the moisture content. Conversely, desorption, inverse process of adsorption, is favoured by an increase of temperature. The Clausius-Clapeyron relation is used to express the heat involved during the sorption process. The latter is called isosteric heat of sorption q_{st} [J.kg⁻¹] and is expressed in Eq. 9 under its general form:

$$q_{st}(u) = -\frac{R}{M_l} \left[\frac{\partial \ln(p_v)}{\partial \left(\frac{1}{T}\right)} \right] \Bigg|_u \quad (9)$$

$p_v = RH.p_{sat}(T)$ [Pa] is the vapour partial pressure with p_{sat} [Pa] the saturated vapour pressure. The index u means that the isosteric heat is determined at constant moisture content. The isosteric heat q_{st} is expressed from the experimental data of sorption isotherms determined at two different temperatures T_1 and T_2 by integrating Eq. (9) between two equilibrium states ($T_1, p_{v,1}$) and ($T_2, p_{v,2}$) defined for any arbitrary constant moisture content:

$$q_{st}(u) = \frac{R}{M_1} \frac{T_1 T_2}{T_2 - T_1} \ln \left[\frac{p_v(T_2, u)}{p_v(T_1, u)} \right] \quad (10)$$

The sorption isotherm at any temperature T is thus determined from an experimentally characterised sorption isotherm $RH(T_{ref}, u)$ as follows:

$$RH(T, u) = RH(T_{ref}, u) \frac{p_{sat}(T_{ref})}{p_{sat}(T)} e^{q_{st}(u) \frac{M_1(T - T_{ref})}{R T_{ref} T}} \quad (11)$$

The isosteric heat of sorption can also be determined from the fitting the experimental data. The model proposed by Powers and Brownyard (PB) is an example [17] and is used in this paper:

$$q_{st}(u) = l_v + \frac{k_1}{(k_2 - u)^{k_3}} \quad (12)$$

where k_1 , k_2 and k_3 are the fitting parameters.

5. Results and discussion

5.1. Hygrothermal properties

The hygrothermal properties of the material remains constant around its value in the dry state for a wide range of moisture content excepted close to the saturation (Table 1). Moreover, these results are in a good agreement with the results of literature.

Parameter	Dry bulk density ρ_0	Vapour permeability δ_p	Saturated moisture content u_{sat}	Liquid absorption coefficient A_w	Open porosity n	Dry thermal conductivity λ_0	Dry specific heat $c_{p,0}$
Value	380±25	3.76 $10^{-11} \pm 3.2$ 10^{-12}	1.09	0.029 ± 0.0058	41	0.076±0.0022	1108 ± 63

Table 1: Main hygrothermal properties of ACC

Figure 2 shows the evolution of the moisture content respectively at 23°C and 10°C. A slight hysteresis may be observed at each temperature. As expected, globally, the warmer the temperature, the lower is the equilibrium moisture content at the same relative humidity. Moreover, the VG model appears here more accurate than GAB model, especially for the high RH than the GAB model to fit the experimental data in adsorption and desorption.

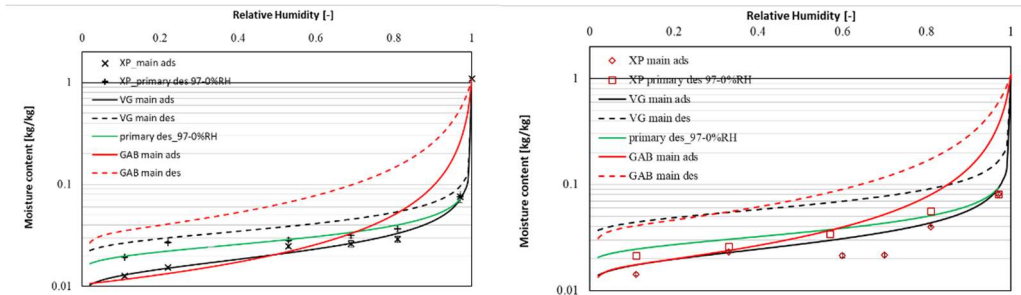


Figure 2: Experimental and modelled sorption isotherms at 23°C (left) and 10°C (right) – comparison between the VG and GAB models

5.2. Hygrothermal response of the material subjected cyclic variations

The evolution of the moisture weight of the S1 samples serie in function of time is presented in Figure 4. As explained in [5], the experimental moisture mass seems to stabilize after the 5th cycle. Moreover, large differences could be observed between the GAB and VG model, whatever the hysteresis phenomenon is considered or not. The VG model appear more accurate to represent the evolution of moisture mass than the GAB model under cyclic relative humidity variations. Moreover, the consideration of the hysteresis phenomenon lead to an improvement of the results especially in desorption phase. The thermodependency of the sorption process have only a slight influence on the evolution of the moisture mass in this study case. Numerical results obtained with the VG model are in good agreement with experimental results during the first cycle, but after the 2nd cycle, strong discrepancies appear. If the global shape of the numerical moisture mass is similar to the one of the experimental moisture data, the numerical amplitude of the moisture mass is strongly lower than the experimental one.

Same trends are observed in figures 5 and 6 for the S2 and S3 samples series.

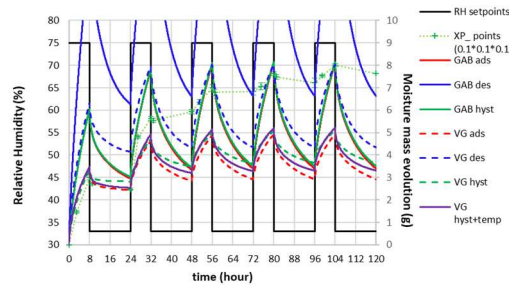


Figure 4: Comparison of the VG and GAB models under cyclic relative humidity variations with and without hysteresis consideration for the S1 samples serie. VG model is also presented with hysteresis and sorption thermodependency consideration

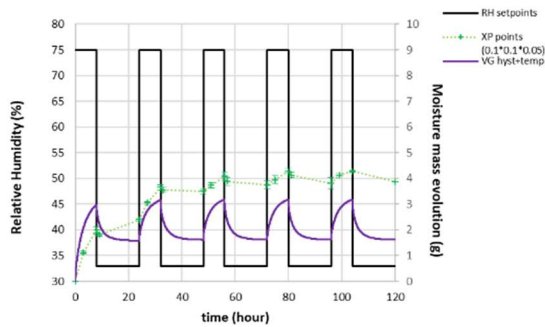


Figure 5: Comparison of the VG model with hysteresis and sorption thermodependency consideration under cyclic variations for S2 samples serie

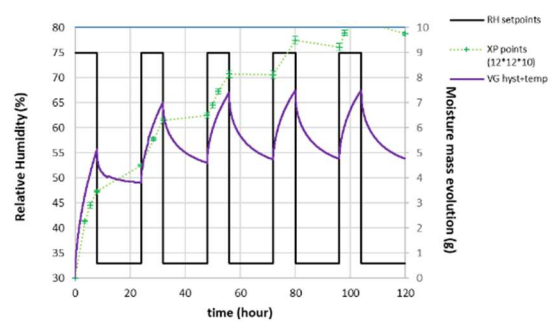


Figure 6: Comparison of the VG model with hysteresis and sorption thermodependency consideration under cyclic variations for S3 samples serie

6. Conclusion and outlooks

The measured experimental hygrothermal properties of the studied ACC performed in this paper are relevant with the data of the literature and bring some new information. They could be used as reference for different studies.

This paper has underlined the need to accurately define the moisture evolution of the material inside the wall. Hysteresis and sorption dependency phenomena improve the results but do not fully explain the discrepancies between experimental and numerical data.

Some complementary studies need to be launched to explain these results.

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Acknowledgements

This work has been supported by the EIPHI Graduate School contract ANR 17 EURE 0002 and by the French National Science Research Center (CNRS) and Region Bourgogne-Franche-Comte for its experimental part.