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Hygrothermal study of lightweight concrete hollow bricks: A new proposed experimental–numerical method

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ABSTRACT

The aim of this paper is the development of a new hybrid methodology to study the moisture transport and heat transfer in masonry structures made up of light concrete hollow bricks (LWHBs) from the numerical and experimental points of view. In order to solve this coupled nonlinear hygrothermal analysis, an instrumented one square meter wall was subjected to eight different moisture stages in the laboratory using a special testing device during a total time of 1480 h. In order to simulate the different experimental stages, steady and transient states were implemented in the finite element models. Furthermore, the design of experiments methodology (DOE) and the goal design optimization (GDO) technique are used to calculate the best optimal parameters from the laboratory tests. Once the optimal parameters have been obtained, the finite element models for each stage are solved so that the moisture and temperature distributions were calculated. In this sense, a very good agreement between the numerical and experimental results is achieved. Finally, the most important conclusions of this study and advantages of this new methodology are exposed.

1. Introduction

The present research work tackles the study of the hygrothermal efficiency of the porous lightweight concrete material (LWHC) [1] and the effect of the moisture transport on the thermal performance of walls made up of lightweight concrete hollow blocks (LWHB) [2,3]. In the framework considered here, light concrete material is more and more recommended by the builders to reach a sustainable development due to their good strength and thermal properties [4,5]. Department of Public Works as well as owners and building proprietors are demanding high-capacity heat-insulating exterior masonry components specifically for further energy savings. For housing as well as in civil and industrial structures, there is also a great interest in light building materials with good physical material behavior, with respect to an energy conscious and ecological design, which fulfills all strength and serviceability requirements, including its thermal and moisture performance.

In recent years, many research works have been published about the exposure of buildings to the driving rain and water penetration [6–8]. These environmental phenomena give place to the decreasing in the facade durability and the hygrothermal behavior [9,10], and therefore reducing the insulation performance and energy savings. With respect to the LWHB's hygrothermal properties, when the density and thermal conductivity are decreased, the porous structure and the hygroscopic sorption are increased. This phenomenon gives rise to an important reduction in the thermal performance of the LWHBs, according to the previous research works [2,11].

Therefore, it is necessary to build a model that allows an accurate and entire description of the coupled problem in relation to the storage and transport of heat and moisture inside lightweight concrete wall. This phenomenon is strongly linked to both temperature and humidity of the surrounding environment as well as its current structure of pores. In this sense, the variations of the external conditions change the temperature in the lightweight concrete mass and the moisture movement within this material. These variations take place until equilibrium is reached between the structure and environment. Both the hygrothermal state of the lightweight concrete and its porous structure causes different mechanisms of moisture transport and storage. The exact description of these phenomena becomes difficult because the most influential factors have both the geometrical and temporal dependence. Taking into account the

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Nomenclature

A	surface of a specific recess or cavity (m^2)
D_m	moisture diffusion coefficient or material diffusivity (m^2/s)
$D_{m_{vap}}$	isothermal vapor diffusivity (m^2/s)
D_θ	thermal moisture diffusion coefficient (kg/(ms K))
e	specimen thickness in the heat transfer direction (m)
F_m	conversion factor for the moisture content (dimensionless)
h_v	latent heat of vaporization (J/kg)
h_{coz}	equivalent moisture film coefficient (s^{-1})
h_{coz}^{Ri}	equivalent moisture film coefficient in the recess "i" (s^{-1})
LWA	lightweight aggregate
LWHB	lightweight hollow brick
m	moisture content (kg/m^3)
Q	heat flux, or heat flow rate through a surface of unit area perpendicular to the direction of heat flow (W/m^2)
q_{conv}	thermal convective flow (W/m^2)
q_{coz}	convective equivalent empirical moisture flow (kg/ms)
q_{rad}	thermal radiation flow (W/m^2)
R	overall thermal resistance (m^2 K/W)
R_{se}	surface thermal resistance of the specimen on the inner face (hot-box) (m^2 K/W)
R_{si}	surface thermal resistance of the specimen on the outer face (lab room conditions) (m^2 K/W)
RH	relative humidity or moisture potential (%)
RMSE	root mean squared error
ΔT	temperature difference between the inner (hot-box) and the outer faces (K)
t	time (s)
U	heat transmission coefficient or thermal transmittance (W/m^2 K)

Greek symbols

λ	thermal conductivity (W/m K)
$\lambda_{50\%}$	thermal conductivity for RH = 50% (W/m K)
λ_{eq}	equivalent thermal conductivity of the brick (W/m K)
ρ	material density (kg/m^3)
ρc	volumetric heat capacity (J/(m^3 K))
θ	temperature (K)
θ_i	wall temperature inside a cavity (K)
θ_j	air temperature inside a cavity (K)

transportation laws, it is possible to derive the differential equations of equilibrium able to describe rightly the key mechanisms of the transport and storage.

In order to solve this problem, a hybrid methodology using numerical and experimental methods in combination has been developed [12–15]. On the one hand, it is necessary to obtain the experimental hygrothermal properties of an instrumented entire wall made up of LWHBs under different moisture contents. On the other hand, the numerical problem implies the solution of two simultaneous nonlinearities [1,3]: the material nonlinearity (i.e., most building materials have variable hygrothermal material properties) and radiation and convection boundary conditions inside recesses (inner holes) of the bricks [14,16,17]. The governing equations that describe the moisture diffusion coupled with the heat conduction in porous solids are well-known [18–20]. To solve this highly nonlinear coupled problem, a goal driven optimization (GDO) approach based on the finite element method (FEM) in combination with the design of experiments (DOE) analysis has been used with success [21–23].

Table 1
Physical properties and mix proportions of the lightweight hollow bricks (LWHBs).

	Corner brick	Normal brick
Height (m)	0.195	0.195
Length (m)	0.5	0.5
Width (m)	0.195	0.195
Mean weight (kg)	13.63	12.80
Real mean density (kg/m^3)	1329	1329
LWA (kg)	3.25	3.06
Silica sand (kg)	8.28	7.80
Cement (kg)	2.00	1.90
Water (kg)	1.50	1.40

Note: LWA (lightweight aggregate): 4–12.5 mm particle diameter (expanded clay).

This research work is structured as follows: firstly, the materials and experimental methods used to carry out this study are described; secondly, the mathematical and numerical models are written; thirdly, the numerical results and the DOE optimization are presented and discussed; and finally, the main conclusions drawn from the experimental and numerical results are exposed.

2. Materials and experimental methods

2.1. Hollow bricks and laboratory tests

The materials used in this research work include lightweight hollow bricks (LWHB) (see Fig. 1(a)) manufactured with expanded clay (main lightweight aggregate), cement and silica sand. The particle size of the expanded clay ranges from 4 to 12.5 mm for lightweight aggregate and from 1 to 5 mm for lightweight sand, respectively. The main properties as well as the overall dimensions of the two types of LWHBs are shown in Table 1 and Fig. 1(a).

With the above indicated LWHBs, a one square meter wall is built and placed over a steel frame in order to check its hygrothermal performance (see Fig. 1(b)). A total of 11 hygrothermal microsensors (see Fig. 1(c)) as well as 7 heat flux sensors with thermocouples (see Fig. 1(d)) are located in this wall at specific places (inner face, outer face and inside wall recesses) (see Fig. 1(e) and (f)) in order to obtain the temperature, relative humidity and thermal fluxes at different locations in the laboratory tests [24,25]. Our laboratory facilities include a climatic air-conditioned system so that the temperature remains constant (about 18 ± 2 °C) during the hygrothermal tests.

With respect to the hygrothermal test, the main stages are as follows (see the flowchart in Fig. 2):

1. *Humidity wall stabilization*: once the wall is built, the wall is placed in our laboratory at its thermal and moisture conditions for 10 days.
2. *Wall drying*: The wall is located in the hot-box apparatus and connected to a special climatic chamber device. A relative humidity of 10% and a 60 °C temperature are kept constant during additional ten days inside the climatic chamber in order to dry the wall. The overall time of the first and second stages (humidity wall stabilization and wall drying) is enough to reach the steady-state conditions (20 days in total). As it is possible to observe in Fig. 3(a), the relative humidity in the inner face (hot-box) remains constant (about 10% of RH).
3. *Thermal conductivity test*: Six stages at different moisture contents (10%, 30%, 50%, 65%, 80% and 90%, respectively) are checked at a constant temperature of 55 °C inside the hot-box.