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HYGROTHERMAL PERFORMANCE INVESTIGATION OF BUILDING LIMESTONES IN VARIABLE CLIMATE

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Abstract

Due to the new challenges imposed by sustainable development, the construction industry is having to rethink its activities. The use of natural stone makes it possible, among other things, to respond to environmental challenges facing the building sector. In addition to its good thermo-hydric properties, the potential of natural stone lies in its production which requires less energy than materials such as concrete, and its durability over time which reduces the need for deconstruction and reconstruction, thus excluding the carbon impact associated with these activities. To promote this natural and environmentally friendly material, it is vital to know its multiphysical characteristics. This research work consisted of studying the thermal and hydric properties of local limestone. The data were then used to numerically simulate the hygrothermal coupling behaviour of this material in an environment of variable humidity and temperature. The simulation results are compared with experimental measurements obtained from limestone blocks exposed to variable climatic conditions. The results show that the limestones studied are sensitive to capillarity and are permeable to water vapour, thereby improving indoor air quality and limiting the risk of condensation and mould growth inside the walls. The numerical model accurately predicted the thermal response of the materials studied.

Keywords: Limestone; Indoor comfort; Hygrothermal properties; Material characterization; Numerical modelling.

1. INTRODUCTION

Until the beginning of the 20th century, natural stone had a social status in building. Due to its good reputation, mainly linked to its aesthetics, mechanical strength, durability over time and thermo-hydric properties, natural stone has undeniable advantages as a building material. Unfortunately, since the industrial revolution and the introduction of new construction materials such as concrete and steel, natural stone has been gradually abandoned [1]. However, to respond to the current environmental challenges, building materials with low environmental impact and high hygrothermal performance become an interesting solution to reduce both CO₂ emissions and energy consumption while ensuring a high comfort for residents.

Limestone, a material widely available locally, particularly in the south of France, and whose exploitation requires reduced energy investment, would make it possible to respond to these sustainable development challenges. According to De Toldi and Pestre, unlike materials such as concrete, the carbon impact associated with the production and maintenance of natural stone is very

low because it does not require by-products for manufacture, but is simply extracted, moved and used. Given the thicknesses of materials generally used (13, 20 and 24 cm for Cross Laminated Timber (CLT), concrete and natural stone, respectively), stone walls will emit respectively 3.06, 2.73 and 1.43 times less than CEM I, CEM III and CLT walls [2]. In addition, the increased durability of limestone greatly reduces deconstruction and reconstruction activities, thereby excluding the carbon impact associated with these activities. Furthermore, little is known about the multiphysical properties and hygrothermal behaviour of limestone, which need to be studied in order to optimize and promote the use of this material. Some works in the literature show that hygrothermal characteristics are strongly influenced by temperature and moisture [3]. On the other hand, the porous structure of a limestone affects its heat transfer and the presence of water in the pores increases the effective thermal conductivity [4]. Tufan and Kun [5] have also shown that increasing porosity increases thermal performance. Indeed, the porous structure would decrease the thermal conductivity due to the presence of air in the pores, which improves the insulation of these materials.

Limestones therefore have the advantage of regulating ambient humidity in buildings and the ability to store and release heat. However, very few studies have simultaneously treated the thermo-physical properties and the consideration of thermal and moisture transfer mechanisms in hygrothermal simulations of limestone. Following this observation, this work proposes an experimental and numerical study of the hygrothermal behaviour of local limestones. They were characterized from a thermal and hydric point of view. Simultaneously, limestone blocks were instrumented and subjected to variable humidity and temperature conditions. The experimental data obtained were then compared with those from the numerical simulations to evaluate the relevance of the predictive model.

2. MATERIALS AND METHODS

This work focuses on limestones from three local quarries in the south of France. The materials studied are the Fontvieille, Estailades and Vers-Pont-du-Gard (VPG) limestones. To understand the hygrothermal behaviour of these limestones, a thermo-hydric characterization campaign was carried out. The main properties studied were thermal conductivity, specific heat capacity, capillarity, vapour permeability and Moisture Buffer Value (MBV). Thermal conductivity was measured using the hot wire method [6]. Specific heat capacity was measured using a Calvet calorimeter (Setaram C80). The capillarity test was carried out by measuring water absorption under the effect of capillary forces according to the standard NF EN 1925. Water vapour permeability was determined using the dry cup method according to the NF EN ISO 12572. The MBV was measured using the NORDTEST procedure [7]. To identify the moisture storage capacity of limestones, sorption isotherms were conducted according to the NF EN ISO 12571.

In a real building wall, heat and moisture transfer mechanisms being coupled, the hygrothermal behaviour of limestones was analysed via experimental and numerical approaches. Experimentally, limestone blocks were instrumented and installed in a wall separating two climatic conditions varying in temperature and humidity. The climatic loads were varied between 0 % and 100 % of relative humidity, and between 0 °C and 50 °C of temperature to remain within the usual conditions. Experimental measurements included temperature and relative humidity at the surface and inside the limestone blocks. Numerically, the 1D model of Künzle [8] was implemented in the COMSOL Multiphysics software. This model describes the coupled heat and mass transfers within an unsaturated porous medium (Equation 1).

$$\begin{cases} \rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + L_v \frac{\partial}{\partial x} \left(\delta_p \frac{\partial}{\partial x} (HR p_{sat}) \right) \\ \xi \frac{\partial HR}{\partial t} = \frac{\partial}{\partial x} \left(K_l \frac{\partial HR}{\partial x} + \delta_p \frac{\partial}{\partial x} (HR p_{sat}) \right) \end{cases} \quad (1)$$

With, T temperature [K]; HR relative humidity [-]; ρC_p volumetric heat capacity [$J.m^{-3}.K^{-1}$]; λ thermal conductivity [$W.m^{-1}.K^{-1}$]; L_v latent heat of evaporation [$J.kg^{-1}$]; δ_p water vapour permeability [s]; p_{sat} saturation vapour pressure [Pa]; $\xi = \partial w / \partial HR$ moisture storage capacity [$kg.m^{-3}$]; w water content [$kg.m^{-3}$]; K_l liquid conduction coefficient [$kg.m^{-1}.s^{-1}$].

3. RESULTS AND DISCUSSION

Table 1 shows the thermo-hydric characteristics measured. Fontvieille limestone has the lowest thermal conductivity because of its high porosity compared with other limestones. This effect is also observed on the volumetric heat capacity, which decreases as porosity increases. Regarding the hydric properties, the limestones studied are sensitive to capillarity and therefore to climatic scenarios with water inputs due to rain and would allow water condensed in the walls to be evacuated. The capillary absorption coefficient varies between $0.33 \text{ kg.m}^{-2}.s^{-1/2}$ and $0.57 \text{ kg.m}^{-2}.s^{-1/2}$ for the three limestones. Thus, the limestones studied have a relatively high capillarity compared to cementitious materials such as concrete [9]. The three stones are also permeable to water vapour and potentially can store/release water by vapour transfer. From the results, Estailades and Fontvieille stones have the highest permeabilities in the order of 10^{-11} s and the VPG stone has a permeability around 10^{-12} s . The order of magnitude of the permeabilities measured agrees with the literature on limestones [3]. In addition, the MBV of three stones are not negligible, and the VPG stone has a better MBV, which can be described as moderate according to the classification defined by the NORDTEST procedure [7]. Thanks to its permeable structure and significant MBV, limestone helps to regulate the relative humidity resulting from internal production linked to human activities such as cooking, showers, etc. This improves indoor air quality. Moreover, this passive regulation also reduces energy consumption and the need for mechanical ventilation systems and dehumidifiers, providing environmental and economic benefits.

Table 1: Thermal and hydric properties of the three limestones studied

Limestone	Total porosity [%]	Thermal conductivity [$W.m^{-1}.K^{-1}$]	Volumetric heat capacity [$kJ.m^{-3}.K^{-1}$]	Capillary coefficient [$kg.m^{-2}.s^{-1/2}$]	Vapour permeability [s]	MBV [$g.m^{-2}.\%RH^{-1}$]
Estailades	30.6	0.986	1545	0.406	1.29×10^{-11}	0.22 - 0.28
Fontvieille	34.5	0.670	1453	0.575	1.04×10^{-11}	0.18 - 0.24
VPG	31.4	0.951	1515	0.327	5.75×10^{-12}	0.50 - 0.60

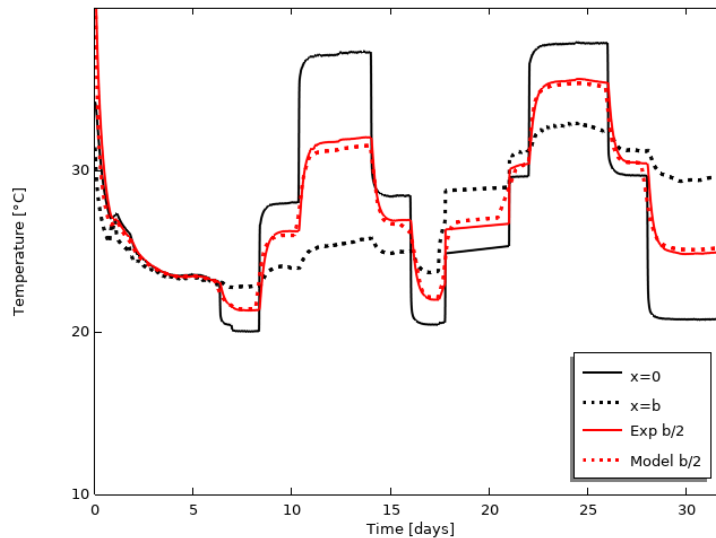


Figure 1: Thermal response as a function of time: experimental versus simulation.

To study the coupling of heat and moisture transfer in limestone, experimental data measured in the centre of limestone blocks are compared with data from a numerical simulation. Figure 1 shows an example of the thermal response (simulation versus experimental) obtained for Estailades limestone, given that the simulation/experimental comparison of other limestones follows the same trend. The solid ($x = 0$) and dotted ($x = b$, b being the thickness of the block equal to 20 cm) black curves represent the boundary conditions. The red curves represent the experimentally measured (solid) and numerically calculated (dotted) temperatures at the centre of the block (i.e. $x=b/2$), as a function of time. The thermal response provided by the model is very close to the experimental measurements, with only a small deviation. These results show that the Künzle model approach can faithfully reproduce the evolution of temperature in an unsteady environment.

4. CONCLUSIONS

The thermal and hydric properties of limestones were characterized and then used to simulate the coupled transfer of heat and moisture in the three limestones. A decrease in thermal conductivity and volumetric heat capacity was observed as the porosity of the limestones increased. In addition, it was observed that the limestones studied are sensitive to capillarity and are permeable to water vapour, potentially could store and release water by vapour transfer. This offers undeniable advantages in terms of comfort for residents, since materials with a water vapour absorption capacity can improve indoor air quality. The comparison between experimental measurements and modelling of the thermal responses of limestone is quite satisfactory. However, the model was applied to blocks composed of a single type of material. Future work should verify the validity of the model on more complex construction systems.

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