Full-scale simulation of indoor humidity and moisture buffering properties of clay

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ABSTRACT:
It is important to control indoor humidity level in buildings as it influences occupant's health and comfort. Some materials, when exposed to the indoor environment, help regulate relative humidity levels due to their capacity to absorb and desorb water vapour. The potential of earthen plasters to improve indoor comfort was investigated through experimentation and simulation. Results of clay moisture buffering capacity and computational simulation of the diurnal moisture variation in a clay plastered test room are discussed. This study compares measurement obtained in the laboratory with simulations output and identifies a discrepancy between the two methods in the quantification of the moisture buffering potential.

Keywords: [earthen plasters, moisture buffering, hygrothermal performance, building simulation]

1. INTRODUCTION

Indoor environment humidity levels have an important influence on occupant health and well-being. Low or high humidity levels influence thermal comfort, the perception of indoor air quality, and increase risks of exposure to bacteria, viruses and mould spores (Arundel *et al.*, 1986). Therefore, Relative Humidity (RH) should ideally be maintained between 40% and 60% (Rode *et al.*, 2005) to optimise indoor quality.

Energy consuming mechanical devices, such as air conditioning systems, are commonly used to maintain optimal RH levels. However, low energy design strategies are needed to provide more comfortable and healthier indoor climates whilst minimising overall energy consumption. One potential solution is the wider use of hygroscopic materials on indoor surfaces, which have the ability to moderate indoor humidity fluctuations through exposure to the room air, potentially reducing operational energy use. In particular, earthen materials, such as finishing plasters and clay masonry, reduce the peaks of internal relative humidity due to their excellent moisture buffering capacity (McGregor, 2014).

In recent years clay plasters have been studied and characterized (Liuzzi *et al.*, 2013; Faria *et al*., 2015; Thomson *et al.*, 2015), showing an increased interest in its dynamic water absorption property. Experimental tests, based on the step-response method such as the NORDTEST protocols (Rode *et al*., 2005), ISO 24353 (ISO, 2008) and JIS A 1470-1 (JIS, 2002), were developed to characterise the moisture buffering effects of materials. These tests methods are applied in a controlled environment, in which temperature is constant and humidity varies cyclically. Material mass variations are continuously recorded to quantify the amount of water absorbed and desorbed during the humidity cycles. The step-response tests do not represent the moisture buffering behaviour of finishing materials in real buildings, due to the influence of ventilation, occupant' behaviour and other factors on the moisture exchange between materials and the environment. It is important to observe the effects of these phenomena on the moisture balance in real buildings. For this purpose, numerical simulations can be useful to evaluate the impact of finishing materials in real buildings.

This paper presents the results of an investigation to quantify moisture buffering capacity of clay and lime plasters. Moisture buffering capacity was experimentally determined, using the NORDTEST step-response tests (Rode *et al.*, 2005). Numerical simulations, based on measured materials characteristics, were used to investigate the response of earthen plasters, and compared to lime plasters, to influence the indoor environmental conditions in a test room. The aim of this study is to highlight the discrepancy between moisture buffering predictions of the numerical model and experimental results.

2. MATERIALS AND METHODS

Samples of commercially available clay and natural hydraulic lime (NHL 3.5, moderately hydraulic lime) were prepared and tested for the study. Finishing surfaces are usually composed of up to 3 mm top coat and a 10 to 15 mm base coat. Maskell *et al*. (2018) demonstrated with clay plasters in the density range of 1700-1870 kg/m^3, only the first 6 to 10 mm of the earthen materials is involved in moisture buffering, which means the sub-layer has a larger contribution to buffer indoor water vapour. Therefore, only undercoat plasters were selected due to their greater volume of involvement to the dynamic water absorption process.

2.1. Specimen Preparation

The clay and lime plasters were prepared by mechanical mixing in the laboratory. To the air dry clay plaster (mix of natural clay < 5 mm and sand 0-2 mm) a further 20% mass of water was added. The lime plasters comprised 1.2:5 (lime: fine aggregate sand) by volume with 30% water added. The mixing water amount was set according to the workability of the plasters. Specimens were cast in 150x150x20 mm moulds made with phenolic-faced plywood. Thereafter the specimens were stored for 28 days before testing in an environmental chamber at 20°C and 60% RH.

a) b)

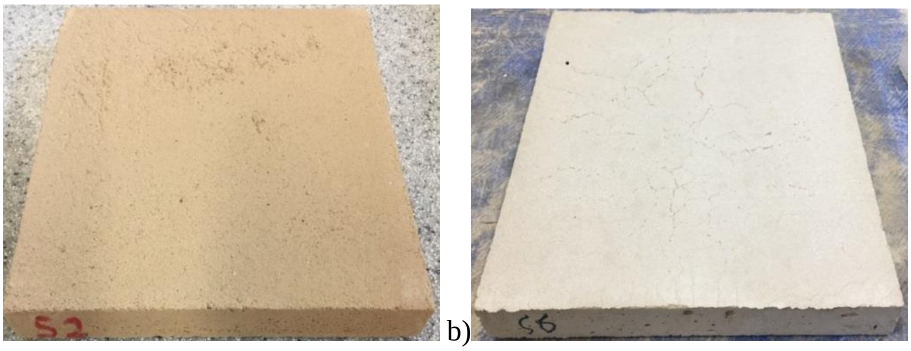


Figure 1: Moisture buffering specimen: a) clay, b) lime

2.2. Density and Vapour Diffusion Resistance Factor

The dry bulk density was measured for the plaster specimens after drying them at 105°C for three days. The vapour diffusion resistance factors were determined in accordance with BS EN ISO 12572 (ISO, 2008), using the dry cup method. Specimens were pre-conditioned in climatic chamber at 23°C and 50% RH for 24 hours. Specimens were afterwards sealed on the top of a plastic container, which contained Calcium Chloride ($CaCl_2$) with 1.5 cm thickness of air layer between salt and internal sample surface. Aluminium tape was used to ensure a vapour tight-seal. The assembly was then placed in a climatic chamber at 23°C and 50% RH and weighted by balance (±0.01 g readability) until constant mass was achieved.

Table 1 presents the measurement results.

Table 1: Dry bulk density (ρ_{dry}), coefficient of variation (CoV) and water vapour diffusion resistance factor (μ)

Material	ρ_{dry} (kg/m^3)	CoV (%)	μ (-)
Clay	1258	2.32	24.45
Lime	1590	1.69	19.62

2.3. Vapour Absorption /Desorption Curve

The sorption isotherm was measured at 23°C and a RH range of 0% to 90% with a Dynamic Vapour Sorption (DVS) apparatus. The experimental accuracy of mass change was ±0.1 mg, temperature was maintained to within ±1% °C and RH to ±1%. Specimens with a mass of approximately 0.3 mg were placed on the DVS scale and the surrounding humidity was increased gradually in steps, measuring the change in mass of the plasters samples.

2.4. Moisture Buffering

The moisture buffering test were performed in a climatic chamber, following the NORDTEST protocol (Rode *et al.*, 2007). Three specimens for each plaster type were pre-conditioned to 50% and 23°C for 24h, until the mass varied by less than 5%. Specimens were exposed to three cycles of 75% RH for 8h and 33% for 16h. Specimens were placed on a mass balance inside the climatic chamber and covered by a screen to reduce the air speed to less than to 0.1 m/s. The mass of each specimen was measured every minute. The Moisture Buffering Value (MBV) is expressed in g/(m^2.%RH).

3. HYGROTHERMAL SIMULATION

3.1. Simulation theoretical model

For thermo-hygrometric simulation of the building, WUFI®Plus V3.0.3 (Wärme- Und Feuchtetransport Instationär) was chosen. In this model the transport of heat and humidity in the building structures is described with the following equations (Künzel, 1995):

$$\frac{dH}{dT}\cdot\frac{dT}{dt} = \nabla\cdot(\lambda\cdot\nabla T) + h_v\cdot\nabla(\delta_p\cdot\nabla(\varphi\, p_{sat})) \qquad (1)$$

$$\frac{dw}{d\varphi}\cdot\frac{d\varphi}{dt} = \nabla\cdot(D_\varphi\nabla\varphi + \delta_p\cdot\nabla(\varphi\, p_{sat})) \qquad (2)$$

where: φ is the relative humidity (-), t is time, T is the temperature (°C), w is the moisture content (kg/m^3), p_{sat} is the saturation vapour pressure (Pa), λ is the thermal conductivity (W/mK), H is the enthalpy (J/m^3), D_φ is the liquid conduction coefficient (kg/ms), δ_p is the vapour permeability (kg/msPa), h_v is the latent heat of phase change (J/kg).

The indoor absolute moisture ratio (c_i [kg / m^3]) is calculated from the following water vapour mass balance equation:

$$V\frac{dc_i}{dt} = \sum_j A\cdot\dot{g}_{wj} + nV(c_a - c_i) + \dot{w}_{\mathrm{Imp}} + \dot{w}_{\mathrm{Vent}} + \dot{w}_{\mathrm{HVAC}} \qquad (3)$$

where: c_a and ci are respectively the absolute moisture ratio of the exterior and interior air, $\dot{g}_{wj}$ is the moisture flux from the interior surface into the room, $\dot{w}_{Imp}$ is the moisture production, $\dot{w}_{\mathrm{Vent}}$ and $\dot{w}_{\mathrm{HVAC}}$ are respectively the moisture gains or losses due to ventilation and HVAC systems.

3.2. Study Case

A single test room, located at the University of Bath's Building Research Park, Wroughton, UK was modelled (Figure 2a). Its internal dimensions are 4m ×3 m and 2.5 m high. The envelope of the structure is a lightweight cavity wall of 404 mm total thickness and comprising of, from outside to inside, exterior concrete block, PIR insulation and aerated concrete blocks (Figure 2b). Floor and ceiling are timber sandwich panel structure of PIR insulation and particle board (total thickness of 350 mm). Walls have a U-value of 0.15 W/m^{2}K, while floor and ceiling have a U-value of 0.10 W/m^{2}K. The internal aerated concrete blocks surface was coated alternatively with clay and lime plaster of 20 mm thickness, whilst the floor, ceiling and door were covered with an impermeable layer (s_d =1500), in order to ensure that the room moisture balance is not affected by the particle board.

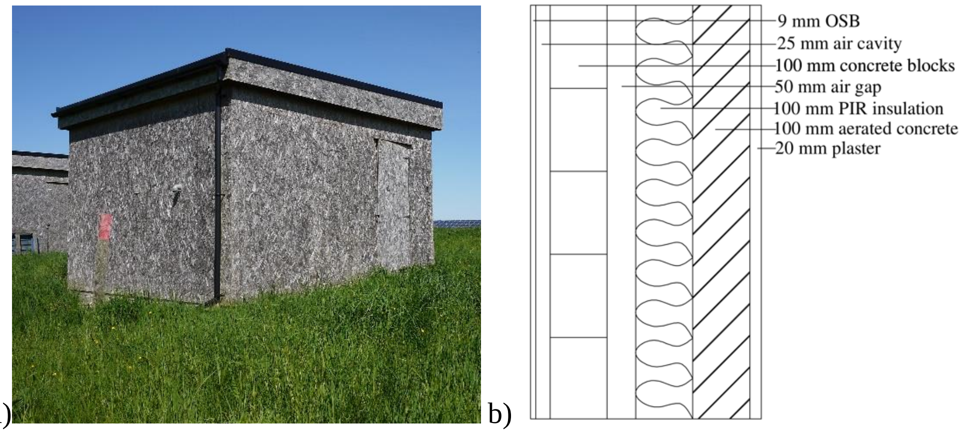
a)  b)

Figure 2: a) test building b) Vertical section of the Concrete Block Masonry wall

The test room was simulated over a two year time-frame. The first year simulation was run without any moisture generation source, as the assembly took one year to reach again equilibrium with the surrounding environment. During the second year the test room had a simulated occupancy of two people during the night, 7 days a week, between 11.00 p.m. to 7.00 a.m. For each occupant a water vapour generation rate in the room was defined as 60 g/h. The natural ventilation rate, in terms of Air Changes per Hour (ACH), was set to a constant 0.5 h^{-1}. The infiltration rate applied to the model was based on the infiltration rate as measured in a previous experimental study of this test cell (Latif *et al.*, 2016), which measured a value equating to 0.0162 h^{-1}. Temperature was kept constant at 23°C. The outdoor climatic data were taken from Lyneham, UK, a weather station at around 10 miles from the location of the test room.

The computational analyses were performed for three simulated wall internal finishes, namely, clay plaster or lime plaster or a vapour barrier (s_d =1500). Plaster hygric properties are reported in

Table 1, while porosity and thermal properties (Table 2) were obtained from a review of published literature; for clay Faria *et al*. (2015) and Thomson *et al*. (2015) and, for lime, Delgado *et al*. (2013) and Černý *et al*. (2006) .

Table 2: Porosity (ε), thermal conductivity (λ) and specific heat (c)

Material	ε (%)	λ(W/mK)	c (J/kgK)
Clay	27.4	1.0	849

Lime	33	1.0	929

4. RESULTS

4.1. Moisture buffering and vapour sorption curve

The sorption isotherm for clay and lime is shown in Figure 3a. Two cycles were performed to ensure the stability of the sorption curves, but only the second curve was analysed. The increase in water content from 0% RH to 90% RH for both materials can be approximated as linear. Clay reached higher values of moisture content, approximately 1.5% mass at 90% RH, compared to the lime (0.7%). However, in each cycle lime gained around 0.08 % mass more than the previous cycle, as the lime binder present may not have completed its hydration. Moisture buffering test results also highlighted that lime did not reach a balance after three cycles. Tests were repeated and an increase of around 3% weight every cycle was observed. Nonetheless, clay has significantly higher buffering performance (Figure 3b): after 8 hours of humidification it reached a MBV of 1.67 g/m^2 %RH, whereas lime reached only 0.95g/m^2 %RH.

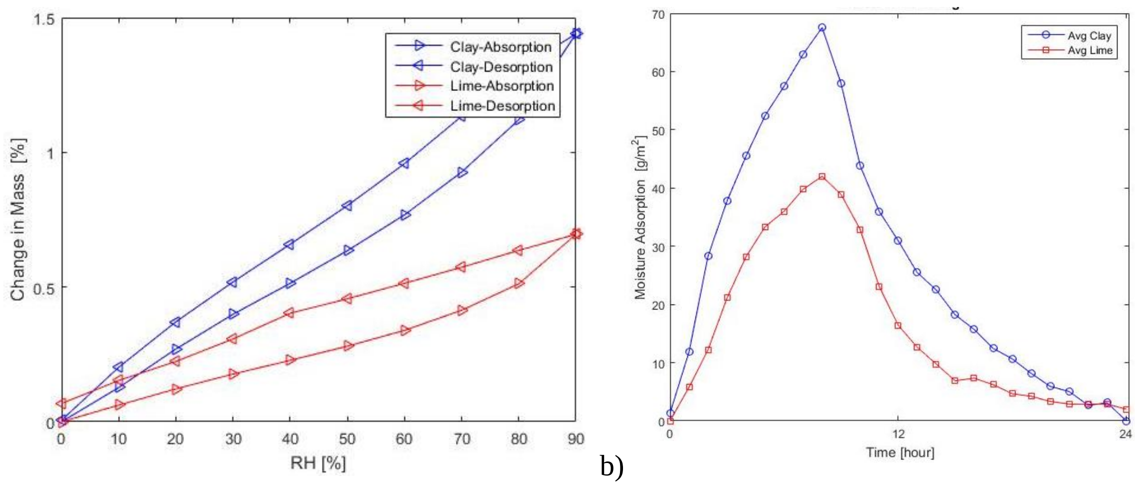
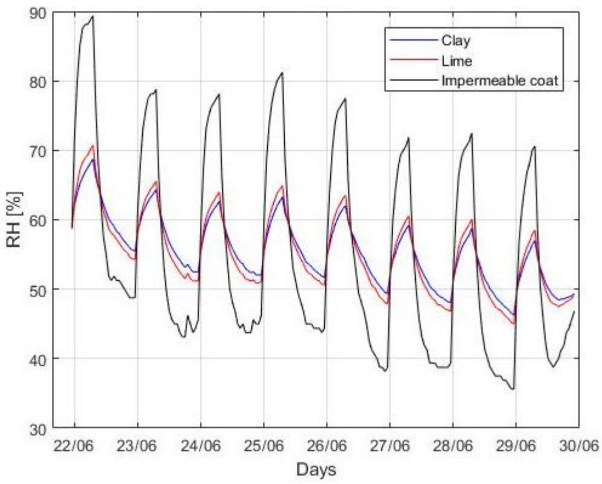
a) 

Figure 3: Sorption isotherm curve and moisture buffering profile of clay and lime

4.2. Moisture Buffering simulation

Simulation results were carried out on all internal walls to compare possible effects of solar radiation, rain and wind direction on the moisture balance of the enclosure. It was noticed that the percentage variation of the moisture content between walls was less than 3 %. For this reason, only the East wall has been reported here. Figure 4 shows the test room absorbed and desorbed moisture in response to humidity generation quite effectively with the lime or clay are applied on internal surfaces. Moisture fluctuation was reduced to 30% RH compared to the impermeable walls case.



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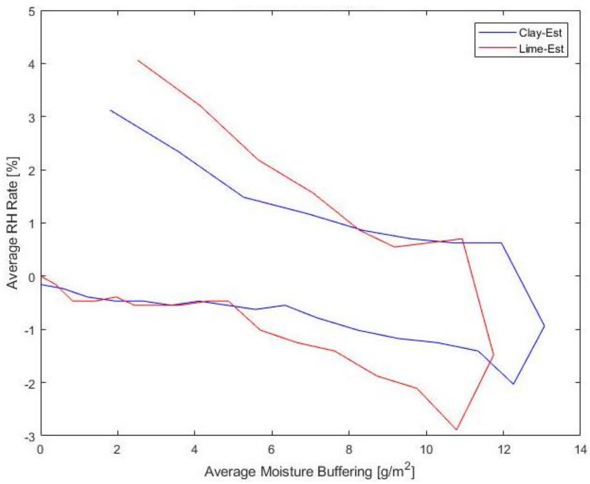

b)

Figure 4: a) RH fluctuation in the simulated room b) RH variation rate over time.

The internal clay plaster, unlike lime plaster, adsorbed a greater proportion of the generated moisture. Figure 4a presents the RH variation in the simulated room and indicates that for clay the average indoor relative humidity peak-to-peak amplitude is reduced to only 10.91% RH in the indoor environment, adsorbing and desorbing each cycle 10.60 g/m^2, whilst lime has a lower buffer potential of 9.24 g/m^2, which corresponds to humidity fluctuation of 13.18% RH. Figure 4b shows also that the average RH in the room varies at a faster rate with lime, than with clay, due to the inferior moisture buffering capacity of lime.

5. ANALYSIS AND DISCUSSION

Experimental results and simulations present similar trends: both indicate the improved moisture buffering behaviour of clay material compared to lime plaster, however, the step-response test overestimated the moisture buffer potential of both materials, as shown in Figure 5. Conceptually, the two analyses are not comparable, as the NORDTEST is performed in a climatic chamber, where relative humidity is controlled and water vapour control inside the chamber depends on the amount of water in the air necessary to keep RH constant. Conversely, in the simulated test room a fixed amount of water is released, independent of relative humidity variations. Consequently, the released moisture amount in the two cases may differ and a volume correction may be necessary; as the climatic chamber has a volume of 0.33 m^3 compared with the room of 30 m^3. However, it was observed that relative humidity fluctuations in the test cell with the impermeable membrane (Figure 4) are similar to the humidity variations recorded in the climatic chamber (around 40% RH fluctuation). For this reason, results were considered comparable.

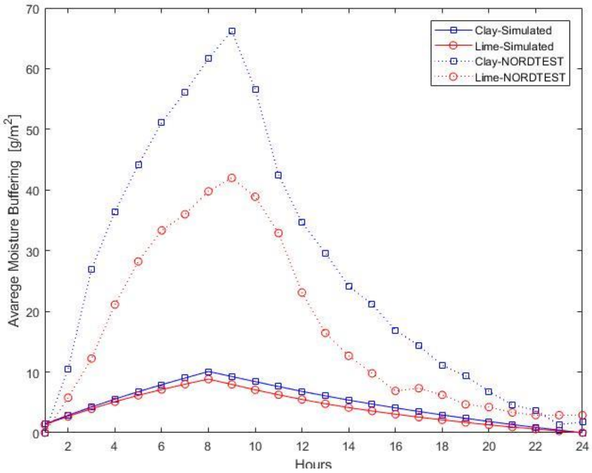

Figure 5: Moisture Buffering comparison: step-response test and simulation results

In Figure 5, significant differences between lime and clay moisture buffering performance is highlighted. The simulation output presents both low average moisture buffering values (g/m^2) and small differences between the two plasters, whilst the results of experimental methods present a much greater average moisture buffering value (g/m^2) and a much higher relative performance of clay plaster, compared with lime plaster. The reasons for such a discrepancy is linked to the interference of other phenomena, e.g. ventilation, infiltration and humidity transport mechanisms in the test room enclosure.

Moisture buffering in a building is strongly dependent on ventilation rate. Depending on vapour pressure differential between the indoor and outdoor, ventilation and infiltrations carry moisture in and out, influencing the maximum absorbed moisture content of the finishing materials. Figure 6a illustrates how ventilation moisture exchange can increase and decrease the moisture buffering potential of the finishing materials: When outdoor vapour pressure is much lower than indoor vapour pressure, ventilation moisture uptake reduces the adsorption potential of materials by 70%.

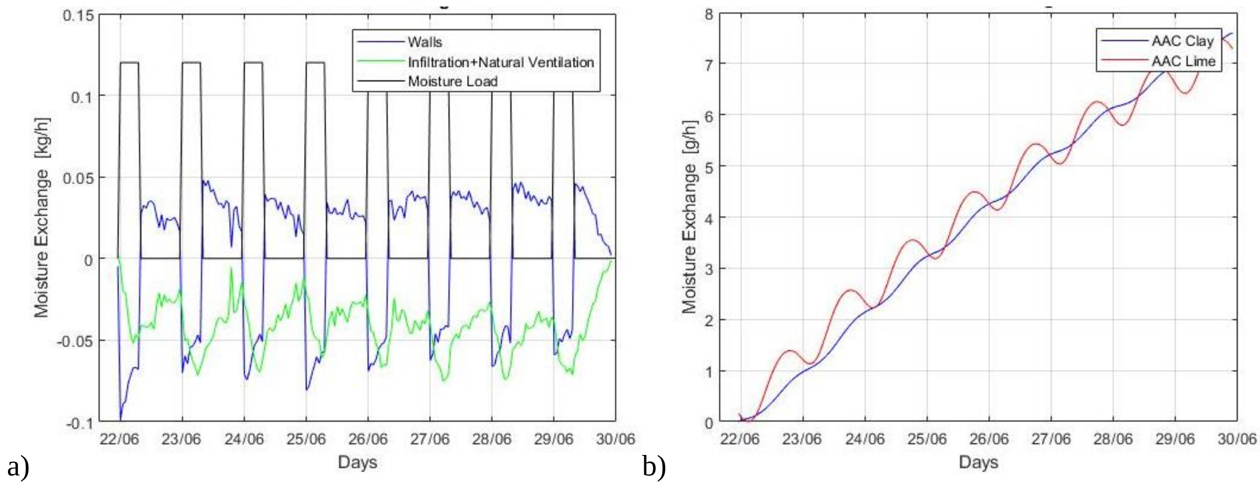

Figure 6: a) influence of ventilation and walls in the moisture exchange with clay plaster b) contribution of the aerated concrete block to moisture buffering

In contrast with values reported in Maskell *et al*. (2018), simulations also show that the Autoclaved Aerated Concrete blocks (AAC), underneath the plaster, are participating in the moisture buffering process. In Figure

6b the moisture exchange between the indoor and AAC is illustrated: the lime plastered simulation case presents daily moisture content fluctuations in the AAC (around 2 g/m^2), which is less marked in the case with clay plaster, due to the higher capacity of the earthen material to absorb water and lower water vapour permeability. The deeper penetration of water into the wall can be linked to the vapour pressure and temperature difference between the indoor and outdoor, as well as to water transport mechanism between different materials. Therefore, further verification using full-scale testing of buildings is necessary.

6. CONCLUSIONS

Moisture buffering capacity of finishing materials was determined both experimentally and through hygrothermal simulations. For the experimental measurement, the step-response method, following the NORDTEST procedure, was performed in a climatic chamber, while a full-scale test room was simulated in WUFI®Plus. Two plasters, clay and lime, were investigated and it is observed that the clay plaster exchange more humidity than lime. However, the step-response test overestimated the moisture potential of both materials, as it does not consider the effect of ventilation on the moisture absorption and desorption of the building surfaces.

Simulation also highlighted that other wall components participated, together with the finishing coatings, to buffer the indoor moisture. According to the computational model, within the daily 8-hour moisture production, moisture reached the AAC block layer, probably due to the vapour pressure and temperature differential between the indoor and outdoor environment. However, this behaviour is in contrast with other studies on the moisture buffering penetration depth and more analysis on the moisture buffering potential of wall assemblies is recommended.

The significance of a direct comparison between full-scale analysis and laboratory-scale material results is to improve moisture buffering testing, optimising material use to increase indoor environment quality. A precise quantification of the material absorbed/desorbed moisture can lead to an improved understanding of the impact of earthen plaster on the hygrothermal comfort and to the consequent reduction of “active” conditioning system energy consumption.

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