Mutual effect between moisture transfer and mechanical response in infill masonry walls of reinforced concrete building envelope

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Abstract: The external envelope of buildings with reinforced concrete structures (RCS buildings) is subjected to environmental actions, particularly related to wind-driven rain (WDR), external humidity variations, and rising dampness, which can cause significant variations in moisture content to their unreinforced masonry (URM) infill walls, mainly associated to water penetration across that envelope. The consequent moisture transfer across the envelope can change the mechanical response of the URM infill walls and lead to their cracking, which could aggravate the referred water penetration, with a subsequent increase in the risk of building envelope degradation. In reverse, the effects of mechanical loads on moisture transfer across that envelope can be also relevant, in terms of change in the moisture content of these URM infill walls.

The aim here is to analyze this type of mutual effect between moisture transfer and mechanical response in URM infill walls of RCS buildings. Essential elements about the characteristics of moisture transfer across URM infill walls and of the interface resistance with moisture flows are summarily described, and the essential evaluation of the mechanical behavior of URM infill walls when subjected to moisture variations is carried out. Moisture transport characteristics are discussed, focusing on analyses of the behavior of masonry elements when subjected to moisture variations. An initial assessment of the mechanical behavior of URM infill walls when subjected to different moisture variations is made through a compression test of a brick masonry specimen with variable moisture content.

Following that analysis, an evaluation is made of the moisture transfer in URM infills, as well as the influence of the interface between layers in that moisture transfer and, subsequently, an assessment is made of hygro-mechanical couplings. Finally, elements for prevention about the causes of degradation of URM infill related to humidity and mechanical actions in the RCS building envelope are discussed.

Key-Words: Infill masonry walls; Moisture transfer; Mechanical behavior; Buildings; Service life

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1 Introduction

The external envelope of buildings with reinforced concrete structures (acronyms: RCS buildings) is subjected to environmental actions, particularly related to wind-driven rain (acronyms: WDR), external humidity variations, and rising dampness, which can cause significant variations in moisture content to their unreinforced masonry (acronyms: URM) infill walls, mainly associated to water penetration across that envelope. The consequent moisture transfer across the envelope can change the mechanical response of the URM infill walls and lead to their cracking, which could aggravate the referred water penetration, with a subsequent increase in the risk of building envelope degradation. In reverse, the effects of mechanical loads on moisture transfer across that envelope can be also relevant, in terms of change in the moisture content of these URM infill walls.

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The transfer of moisture within the walls can change significantly the deformations and stresses of URM infill walls. Therefore, it is important to identify the critical aspects of that transfer associated with moisture variations, particularly related to water penetration inside the walls due to rainwater and rising dampness. Due to these moisture variations, the elements of the building envelope can be subjected to relevant deformations and volume changes, [1], which can lead to the degradation of URM infill walls and of the aesthetic aspect of the building envelope, with a negative impact on the safety, level of comfort and durability of the building, [2]. Moisture can also cause degradation indirectly, when damage occurs due to the crystallization of salts transported by the water, inside the masonry, [3].

Masonry units (particularly, clay bricks and concrete units) usually expand when wet and shrink when dry, and, therefore, the dimensional and weight variations of masonry units subjected to moisture and temperature changes can occur in case of environmental actions on the building envelope, [4]. Moreover, the heat capacity of a porous material, such as the case of masonry units, is associated with its moisture content. The moisture influence on the thermal conductivity of a wet porous material is often given as a linear relationship based on experimental values determined for different moisture content conditions.

The moisture transport in the multi-layered construction elements of buildings could present a significant deviation relative to the moisture transport that could be found in single material elements, and this deviation is referred, essentially, to a retardation of the liquid transport across the material interface [5]. In the particular case of masonry, the phenomena of retarded water uptake across a brick–mortar interface is complex to analyze due to the multiple causes that can be attributed to above-referred deviation, and the incorporation in numerical models usually is based on a simplified implementation of the referred phenomena, and different correspondent approaches were developed. An agreement between numerical and experimental investigations was obtained, in a widely used approach, [6], by assuming a perfect hydraulic interface contact in combination with modified mortar properties. In another approach, checking previously the type of liquid transport across the interface between masonry blocks and mortar, the subsequent simulation of the moisture behavior was made through the use of an interface resistance, and the change in material properties was neglected, [7]. Differently from the previous approach, a change in mortar properties is taken into account in a methodology which considers also interface resistance, [3], and determines the brick–mortar interface resistance based on the water uptake from the bricklayer into the mortar joint. Therefore, the values are obtained for the liquid transport into a material with a lower absorption, when compared to the first material layer, [3]. Similar results to the last approach were obtained in another method, which determined analytically interface resistances, [8].

2 Need for improved knowledge about moisture transfer and mechanical response in URM infill walls and the methodology of the present study

The presence of moisture in the building envelope can have a relevant impact on the energy efficiency and service life of buildings, as well as on their indoor climate and air quality, which justifies an adequate understanding and control of moisture in buildings. The moisture-related processes, particularly the mechanisms of transfer of moisture within the building walls, have multifaceted characteristics, due especially to the respective physical processes of absorption, condensation, and capillarity in the constituent materials of these walls.

The effects of moisture on the mechanical behavior of URM infill walls can be significant, (particularly, stress variation, creep, volumetric changes, and cracking) and damage. Conversely, the mechanical effects on moisture transfer, in the reverse coupling, can be relevant in terms, especially, of change of moisture transport. However, there is still a need for a better understanding of the hygro-mechanical behavior of URM infill walls.

That highlights the importance of deep knowledge regarding this type of interaction between moisture variations and mechanical behavior of URM infill walls, particularly comprising the assessment of the respective linear and non-linear mechanical behavior.

The main motivation behind this work is to study more deeply the mutual effects between moisture transfer and mechanical response in URM infill walls of RCS building envelope.

Taking into account the referred need for improved knowledge regarding that type of mutual effects, the methodology of the present study will consist of the analyses of this type of mutual effect between moisture transfer and mechanical response in infill masonry walls in reinforced concrete buildings.

Essential elements about the characteristics of moisture transfer across infill masonry (URM) and of the interface resistance with moisture flow basic are summarily described, and the essential evaluation of the mechanical behavior of URM infill walls when subjected to moisture variations is carried out. Moisture transport characteristics are discussed, focusing on the analyses of the behavior of masonry elements when subjected to moisture variations. An initial assessment of the mechanical behavior of URM infill walls when subjected to different moisture variations is made through a compression test of a brick masonry specimen with variable moisture content.

Following that analysis, an evaluation is made of the moisture transfer in URM infills and the influence of the interface between layers in that moisture transfer. Subsequently, an assessment is made of hygro-mechanical couplings through a basic approach to the influence of moisture on the mechanical response and the evaluation of mutual effects between moisture transfer and mechanical response. Finally, elements for prevention about the causes of degradation URM infill related to humidity and mechanical actions in RCS building envelope are discussed.

3 Essential characteristics of the moisture transfer across URM infill walls or respective interfaces and of their mechanical behavior when subjected to moisture variations

The external humidity variations can influence significantly the global behavior of the URM infill walls of the building envelope, leading to a relevant movement of moisture through the building. Building performance can change especially as the result of variations in the moisture content of these walls and of their consequent dimensional changes.

The hygric properties of porous building materials are essential information for the assessment of moisture-related processes, [9], and these properties are usually determined through experimental characterization (testing), particularly including the capillary absorption test, which determines the capillary absorption coefficient A_{cap} ($kg.m^{-2s-0.5}$) and the capillary moisture content w_{cap} ($kg\cdot m^{-3}$).

Complementary, using non-destructive techniques (for example, X-ray or NMR) for analyzing moisture content profiles in the sample material, the moisture diffusivity (and permeability) can be determined, [8]. Otherwise, the sorptivity S ($m\cdot s^{-0.5}$) can be determined from the capillary absorption test. A_{cap} is directly related to S ($A_{cap} = S.\rho_w$; ρ_w ($kg\cdot m^{-3}$) – density of water).

The impact of material interfaces on moisture absorption in masonry is a complex matter that requires the characterization of material interfaces.

The basic description of the moisture transfer in the porous media, the influence of the interface between layers in moisture transfer, and the mechanical behavior of URM infill walls, when subjected to moisture variations, are, in the following, summarily analyzed.

3.1 The moisture transfer in the porous media

The moisture transfer in the porous media has been currently modeled as a pure diffusion process, considering relative humidity ϕ as the moisture driving potential, [10], and where vapor diffusion and liquid water transfer are described, by Fick's law, and treated as two independent processes, without interaction between them (capillary transfer of liquid water could be assumed as a flow); or, in another current type of modeling, the temperature and relative humidity are used as the driving potentials, the vapor diffusion is also described by Fick's law, but the liquid water transfer is described by Darcy's law (moisture diffusivity is assumed to contain two components: liquid water transfer and water vapor diffusion), [10]. In both current types of modeling, above referred, concerning the storage of heat and moisture, the same physical description is applied, the moisture driving potential is relative humidity and is continuous at the interface of a multilayer wall, heat of the gaseous phase is negligible, and moisture storage is not significantly influenced by temperature, [10].

About the liquid transport, as an example, for the first type of modeling, the equation that intends to describe the referred liquid transport, briefly, is presented, in the following, [11], [10].

$$\frac{\partial w}{\partial \phi}.\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial x}\left(Dw.\frac{\partial w}{\partial \phi}.\frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial x}\left[\frac{\delta_a}{\mu}.\frac{\partial \phi.Psat}{\partial x}\right] \quad (1)$$

φ (%) - relative humidity;
w (kg/m^3) - moisture content;
μ - water vapor diffusion resistance factor;
δ_a - [kg/(m·s·Pa)] - water vapor permeability of stagnant air;
t (s) - time coordinate;
P_{sat} (Pa) - saturated water vapor pressure;
D_w (m^2/s) - moisture diffusivity of material (this coefficient depends, particularly on the material and transport process; capillary absorption; and capillary moisture content).
Where δ_a is given as follows:

$$\delta_a = \frac{2x\,10^{-7}.(T + 273.15)^{0.81}}{P_{ambient}} \quad (2)$$

T (K) – temperature;
$P_{ambient}$ (Pa) - ambient atmospheric pressure, which is a function of temperature T (K).

Relatively to the boundary conditions, solar radiation is considered the external heat boundary condition, [11], [10]. The outer and inner surface boundary conditions are given by Eqs. 3 to 6 (the subscript e/i refers to the exterior/interior surface of the wall).

$$g_{n,e} = \beta_{p,e}(\phi_e.p_{sat,e} - \phi_{surfe}.p_{sat,surfe}) \quad (3)$$

$$q_{n,e} = h_e(T_e.T_{surfe} + h_{1v}.g_{n,e} + \alpha.q_{solar}) \quad (4)$$

$$g_{n,e} = \beta_{p,i}(\phi_i.p_{sat,i} - \phi_{surfi}.p_{sat,surfi}) \quad (5)$$

$$q_{n,i} = h_i(T_i.T_{surfi} + h_{1v}.g_{n,i}) \quad (6)$$

ϕ_e - relative humidity of outdoor air;
T_e (K) - temperature of outdoor air;
ϕ_i -relative humidity of the indoor air;
T_i (K) - temperature of indoor air;
g_n (kg/(m^2·s) - moisture flow through the wall surface;
q_n (W/m^2) - heat flow across the surface;
β_p (kg/(m^2.s.Pa)) - vapor transfer coefficient at the surface;
ϕ_{surf} - relative humidity at the surface;
p_{sat} (Pa) - saturation water vapor pressure of air;
$p_{sat;surf}$ (Pa) - saturation water vapor pressure on the surface;
h (W/(m.K)) - heat transfer coefficient at the surface;
T_{surf} (K) - temperature at the surface;
α - solar absorptivity of the exterior surface of the exterior wall;
q_{solar} (W/m^2) - solar radiation;

3.2 Liquid transport across the material interface between layers

A building infill wall, usually, consists of multiple layers, and the moisture transport inside it can be difficult to analyze, because masonry is a composite material made with bricks/blocks and mortar adjusted in many different bonding (vertical and horizontal mortar joints). Usually, the wall section can correspond to a single leaf or two leaves of different thicknesses, which can be connected or separated by an internal layer, filled with insulation material, or not filled at all (void space). Moisture transport in multi-layered elements can diverge from the moisture transport corresponding to the group of single material elements, mainly in terms of retardation of the liquid transport across the material interface, [3], [5].

Nevertheless, masonry could approximately be considered a homogeneous continuum, if suitable brick/block characteristics properties are adopted, aiming to reproduce different possible behaviors associated with likely values of water absorption. The impact of interfaces on water absorption in masonry is appreciable and evident through the results of relevant experimental studies on this subject, [3], [9].

Moisture flow across the interface g_{IF} (kg/(m2·s)) could be given by the following expression, [6]:

$$g_{IF} = K_{IF}\frac{\partial P_c}{\partial x} \quad (7)$$

K_{IF} (s/m) - interface permeability;
P_c (Pa) - capillary pressure.

It is assumed, in the above relation, that the brick-mortar interfaces have an imperfect contact for moisture transport.

The interface resistance can be modeled as an air layer between materials, according to the following equation [6]:

$$R_{IF} = \frac{h}{\delta_a}.\frac{\partial p_c}{\partial p_v} \quad (8)$$

R_{IF} (m/s) - interface resistance;
h - height of air layer (m);
δ_a - vapor diffusion coefficient for still air (s);
P_c - capillary pressure (Pa);
P_v - vapor pressure (Pa).

The interface resistance can also be modeled as an explicit infinitesimal layer, [3], [8]. A type of characterization of material interfaces with interface resistances, broadly used, takes into account an interface resistance and the change in mortar characteristics, determining the brick–mortar interface resistance based on the water uptake from the bricklayer into the mortar joint, [3], [8].

Capillary water uptake in masonry can be determined, approximately, with the sharp-front-theory, which assumes that real smooth moisture fronts can be simplified to sharp separations between the wet and the dry material zone, [8]. Based on that theory, moisture accumulation during capillary water uptake into a two-layered composite could be expressed in terms of the absorbed moisture mass per unit surface area *m* (kg/m^2), as follows, [8]:

$$m = A_{cap,1} \cdot t^{0.5} \qquad t \leq (L_1 \cdot f_1 / S_1)^2 \tag{9}$$

$$m = A_{cap,2} \cdot \tau^{0.5} + w_{cap,1} L_1 - w_{cap,2} L_E \qquad t > (L_1 \cdot f_1 / S_1)^2 \tag{10}$$

Where L_E and τ are defined as follows:

$$L_E = L_1 \cdot (K_2 / K_1) \tag{11}$$

$$\tau = t + \left(\frac{w_{cap,2} \cdot L_E}{A_{cap,2}}\right)^2 - \left(\frac{w_{cap,1} \cdot L_1}{A_{cap,1}}\right)^2 \tag{12}$$

A_{cap} (kg/m²s$^{0.5}$) - capillary absorption coefficient;
w_{cap} [kg/m³] - capillary moisture content;
t [s] - actual time;
τ [s] - shifted time;
K [s] - front permeability;
L [m] – length;
L_E [m] is material1's equivalent length (hydraulic resistance of layer 1 expressed as a length of layer 2).

Joint mortar's capillary absorption coefficient and the equivalent length of the underlying brick facet can be obtained through the application of the procedure, that is, in the following, presented, [8]. Regarding brick and mortar capillary moisture contents, the capillary moisture contents of brick and mortar $w_{cap,1}$ and $w_{cap,2}$ are given by the averaged maximal moisture contents reached in the brick and mortar, [8]. In respect to the front location of brick and mortar moisture, by taking the location of half the capillary moisture content as representative for the position of the 'sharp' moisture front, the moisture content profiles are translated into a relation between front location and time, [8]. Concerning the brick capillary absorption coefficient, the multiplication of the moisture front location in the brick with its capillary moisture content results in the evolution of the total absorbed moisture mass per unit surface *m* with time *t*. Least-squares approximation with Equation (5) gives the brick capillary absorption coefficient A_{cap1}. Relatively to the mortar capillary absorption coefficient and brick equivalent length, least squares approximation of the evolution of the moisture front location in the mortar joint with time, ultimately, yields the mortar's capillary absorption coefficient $A_{cap,2}$ and the brick's equivalent length L_E, [8].

3.3 Mechanical behavior of URM infill walls when subjected to moisture variations

The exposure to environmental actions, particularly related to the increase of moisture variations in building walls, has a degrading effect on the mechanical response of the material. As regards the influence of moisture on the mechanical response, the elastic properties and strength of the masonry may decrease due to the presence of moisture, [12]. That negative impact on the mechanical response can be caused, especially, by the increase of internal stresses and dimensional changes in these walls, that lead to a possible decrease of mechanical resistance associated with cracking (damage).

Particularly wind-driven rain can subject the external envelope of buildings to relevant mechanical loads, together with excessive vertical deformations of the supporting reinforced concrete (RC) elements of URM infill walls, and could affect the out-of-plane (OOP) capacity of URM infills related to wind action, in terms of appreciable detrimental effects in the resistance of the connections of the URM infills, [13].

Moreover, degradation, weathering, and spalling due to salt crystallization (which has motivated intense research about salt transport and crystallization in porous materials, [3]) of the building envelope can be related to these moisture variations.

The mechanical performance of porous materials is generally influenced by moisture, which can cause a decrease in the mechanical characteristics, [12]. The presence of moisture can modify the linear and non-linear behavior of the URM infill walls, [12], as well as the mechanical characteristics, such as Young modulus, strength, and friction angle, and cause damage due to the dissolution of mortar joints.

RCS buildings subjected to environmental actions during their service life, especially to humidity variations, can affect URM infill walls as well as RC elements. The environmental actions can alter the normal stress distribution associated with gravity loads alone and induce localized concentrations of compressive and tensile stresses. Regarding the RC elements, time-dependent deformations of concrete have a coupled character, particularly with moisture variations that can induce volumetric changes and can cause alterations in their material properties, specifically in their mechanical characteristics, [14]. Moisture-related shrinkage in concrete is associated with the change in hygral conditions that causes a volumetric change of the material, and the hygral state in concrete can be affected by ambient conditions causing drying shrinkage, [14].

Concerning coupled hygro-mechanical behavior it is important to evaluate the effect of the moisture field on the mechanical response and include the effect of the reduction of mechanical strength related to the moisture transport process.

4 Analysis of brick masonry walls subjected to moisture variations and varying vertical loads

An initial assessment of the mechanical behavior of URM infill walls when subjected to different moisture variations and varying vertical loads is made through a compression test of a brick masonry specimen with variable moisture content, [1].

The description of a compression test in a masonry specimen M1 with variable moisture content, as well as the depicted respective test results and correspondent analysis and discussion, are, in the following, presented.

4.1 General description of the Specimen M1 test setup

A compression test was made in a masonry specimen M1 with variable moisture content, [1]. Specimen test M1 (Figure 1) was built with massive ceramic bricks (bricks with approximate values of Gross dry density ($\rho_{g,u}$): 2100-2300 kg/m^3; and of Water absorption (W_s):15%-20%), which have average dimensions of approximately 213 mm (length) x 108 mm (thickness) x 60 mm (height), and cement mortar joints (cement sand ratio - 1: 4 / volumetric ratio). Masonry specimen M1 was subjected to three loading phases of axial compression, until it reached, in the third loading phase, a state of significant cracking, without reaching a global collapse.

Fig. 1: Aspect of face A of Specimen M1 before the test (at the left side of the figure); a schematic representation of the specimen (at the right and superior side of the figure); aspect of a brick (masonry unit) used in the execution of the specimen M1 (at the right and inferior side of the figure)

At the beginning of the test (Day 1), the specimen, in dry condition, was slightly loaded (pre-loaded correspondent to 10 kN (0.212 MPa) of axial compression load) and then was discharged. Subsequently, the specimen was weighed (Figure 2), before going into a phase of complete immersion in water, for approximately 12 hours (Figure 3). Immediately after the end of immersion in water, the wet specimen was again weighed. After the referred process of weighting, the specimen was, on the same day (Day 1), subjected to a second loading phase. In this second loading phase, a gradual axial compression load was applied, with loading steps of 10 kN, 20 kN, 40 kN, 60 kN, 80 kN, 100 kN, 120 kN, 140 kN, 180 kN, and 300 kN; then the loading phase was halted.

Fig. 2: The phase of the weighting of the Specimen M1 (dry state – 1st Phase of the test) in a digital balance

Fig. 3: The phase of immersion in water during 24 hours of the Specimen M1

The third phase of the test was initiated after a period of six days of drying of the specimen in the laboratory with controlled ambient and subsequent to the previous loading phase (2nd Phase was initiated 6 days before 3rd Phase), and, before the application of load, the specimen was again weighed. In the third loading phase, a gradual axial compression load was applied to the specimen in a dry state, with loading steps of 10 kN, 120 kN, 180 kN, 300 kN, 420 kN, 540 kN (11.44 MPa) and final load of 660 kN, corresponding to the end of this loading phase.

During the three loading phases, for each loading step, after reaching the corresponding load, the specimen was discharged, and immediately after that discharge, the horizontal and vertical residual deformations were measured with an alongameter (Figure 4 and Figure 5), registering the residual deformations after load. The frame points for horizontal and vertical deformation measurements (points A1 to A6) in face A of Specimen M1 in the compression test are represented in Figure 4.

Fig. 4: The phase of preparation of the Specimen M1 for the 1st phase of the compression test

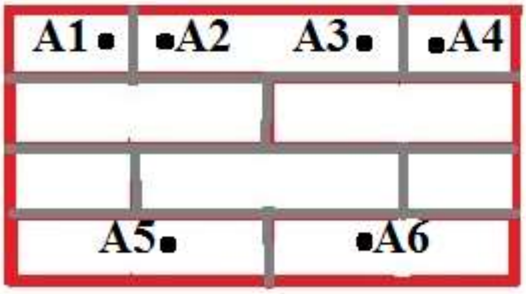

Fig. 5: Schematic representation of the frame points for horizontal and vertical deformations measurements (points A1 to A6) in face A of Specimen M1 for the compression test

In the following, essential aspects of the results of the test of specimen M1 are analyzed, related to the observed values of deformations (vertical and horizontal) of the specimen, focusing especially on the 1st Phase and 2nd Phase of the test, for two situations: after an applied load of 10 kN, in dry situation, during the 1st phase (Figure 6 and Figure 7); for different loading steps of applied load, after water immersion, in wet situation, during the 2nd phase of the test.

Fig. 6: Aspect of face A of Specimen M1 before the compression test

Fig. 7: Aspect of face B of Specimen M1 before the compression test

4.2 Test results of specimen

The specimen, in dry condition, after being slightly loaded (pre-loaded correspondent to 10 kN of axial compression load), and then discharged, the specimen was weighed, and a value measured of 28830 g of weight (Table 1) was obtained, before going to above referred phase of complete immersion in water. After removing from immersion, the wet specimen was again weighed, and a value of 30856 g of weight was registered (Table 1), corresponding to an increase of moisture content of 7.1%, relative to the previous weighting of the dry specimen. Then, the specimen was subjected to a second loading phase (2nd Phase - Figure 8). Before the application of load, in the third loading phase, the specimen was weighted, and a value of 29457 g of weight was registered, correspondent to an increase of moisture content of 2.1%, relative to the dry specimen, and to decrease of 4.5% relatively to the previous weighting, after immersion (Table 1).

The third loading phase was initiated 6 days after the previous loading phase (Figure 9) and, before the application of load, the specimen was again weighted and a value of 29457 g of weight was registered, correspondent to an increase of moisture content of 2.1% relatively to the dry specimen, and a decrease of 4.5% relatively to the previous weighting, after immersion.

Table 1. Description of actions related to the modification of moisture content of Specimen M1 (drying and wetting) and results of weighting the specimen.

State of the specimen	Days after the start of the test of 1st phase (aplication of 10 kN)	Weight of the specimen	Change of moisture content – Mass variation (%)*
Dry condition	Day 1	28830 g	-
Immediately after the end immersion in water during 12 h	Day 2	30856 g	+7.1%
Six days after the end of immersion in water	Day 7	29457 g	+2.1%

* Relatively to the start day of the test (Day 1) - dry specimen

The results of the measurement of horizontal and vertical residual deformations in specimen M1 corresponded to an increase of values, from a dry state (Day 1) in the 1st Phase (Figure 10), to a wet state, after immersion (24 hours) in the 2nd Phase, for a load step of 10 kN (Figure 11). Besides, horizontal and vertical residual deformations revealed a decrease of values horizontal and vertical residual deformations, in 3rd Phase (Figure 12), registered for a dry state, after six days of drying in the laboratory with controlled ambient, for 10 kN of load, relative to the values registered in the previous 2nd phase, for the same load step of 10 kN.

Fig. 8: Aspect of Specimen M1 after the loading step of 180 kN, in the 2nd phase of test

Fig. 9: Aspect of face A of Specimen M1 after the loading step of 660 kN, in the 3rd phase of test

Table 2. Horizontal deformations in the test of Specimen M1

State condition	Load		A2-A5	ε_{Hm}	A3-A6	ε_{Hm}
(dry/wet)	kN	MPa	dh1	mm/m	dh2	mm/m
Dry state (Day 0)	0	0	1967	0	1968	0
	10	0,212	1968	-0,000005	1966	0,00001
Wet state (Day 1) - after immersion (24 hours)	0	0	1955	0	1958	0
	10	0,212	1954	0,000005	1954	0,00002
	20	0,424	1955	0	1956	0,00001
	40	0,848	1953	0,00001	1954	0,00002
	60	1,271	1948	0,000035	1945	0,000065
	80	1,695	1943	0,00006	1943	0,000075
	100	2,119	1942	0,000065	1936	0,00011
	120	2,543	1930	0,000125	1930	0,00014
	140	2,966	1927	0,00014	1920	0,00019
	180	3,814	1920	0,000175	1908	0,00025
Dry state (Day 7)- After a period of six days of drying in laboratory with controlled ambient	0	0	1878	0	1820	0
	10	0,212	1876	0,00001	1816	0,00002
	60	1,271	1873	0,000025	1813	0,000035
	180	3,814	1863	0,000075	1802	0,00009
	300	6,356	1857	0,000105	1792	0,00014
	420	8,899	1853	0,000125	1777	0,000215
	540	11,442	1868	0,00005	1746	0,00037
	660	13,984	1900	-0,00011	1720	0,0005

Unity=0.001 mm; Base of measurement = 200 mm

Table 3. Vertical deformations in the test of Specimen M1

State condition	Load		A1-A3	ε_{Vm}	A2-A4	ε_{Vm}
(dry/wet)	kN	MPa	dv1	mm/m	dv2	mm/m
Dry state	0	0	1968	0	2040	0
	10	0,212	1965	0,000015	2037	0,000015
Wet state - after immersion (24 hours)	0	0	1958	0	2030	0
	10	0,212	1953	0,000025	2031	-0,000005
	20	0,424	1953	0,000025	2022	0,00004
	40	0,848	1948	0,00005	2014	0,00008
	60	1,271	1947	0,000055	2005	0,000125
	80	1,695	1940	0,00009	2004	0,00013
	100	2,119	1940	0,00009	2000	0,00015
	120	2,543	1935	0,000115	1997	0,000165
	140	2,966	1930	0,00014	1994	0,00018
	180	3,814	1920	0,00019	1987	0,000215
Dry state - After a period of six days of drying in laboratory with controlled ambient	0	0	1848	0	1998	0
	10	0,212	1848	0	1995	0,000015
	60	1,271	1845	0,000015	1988	0,00005
	180	3,814	1840	0,00004	1982	0,00008
	300	6,356	1821	0,000135	1986	0,00006
	420	8,899	1784	0,00032	1978	0,0001
	540	11,442	1724	0,00062	1961	0,000185
	660	13,984	1640	0,00104	1929	0,000345

Unity=0.001 mm; Base of measurement = 200 mm

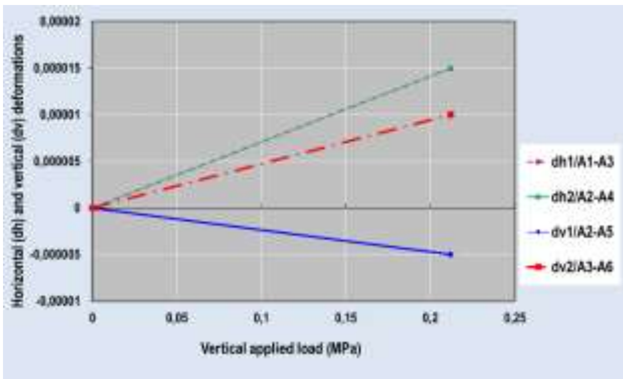

Fig. 10: Values of deformations of the specimen M1 during 1st loading phase, for the vertical applied load

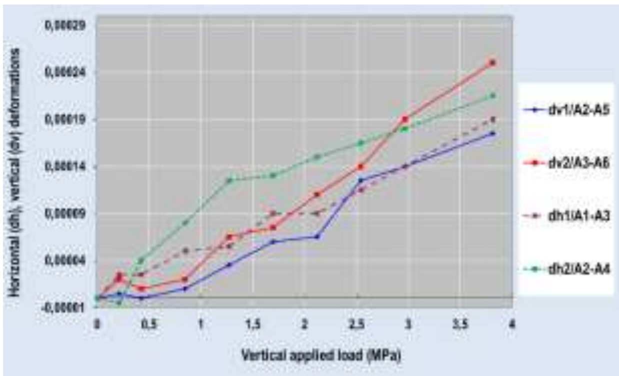

Fig. 11: Results of deformations (dv1, dv2, dh1, dh2) of the specimen M1 during 2nd loading phase, for the vertical applied load

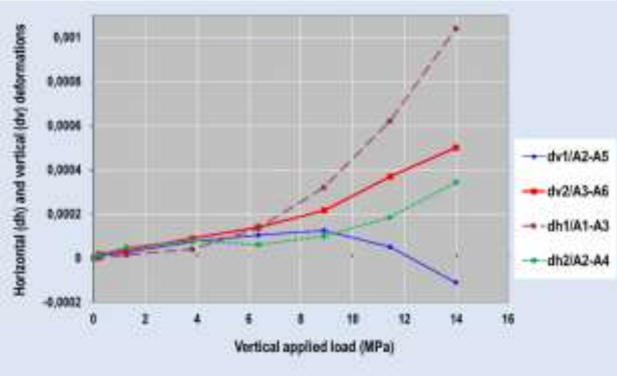

Fig. 12: Results of deformations (dv1, dv2, dh1, dh2) of the specimen M1 during 3rd loading phase, for the vertical applied load

4.3 Discussion of the results of the test of Specimen M1

The results of the measurement of deformations with an alongameter in specimens show that the variation of horizontal residual deformations (A1-A3; A2-A4: see reading points in Figure 10) and vertical (A2-A5; A3-A6: see reading points in Figure 10), measured after discharge of the specimen, at the end of each load step, were generally correspondent to a gradual expansion of the specimen

Confronting the results of deformations (dh1, dv1, dv2) of specimen M1 during 1st Phase, when the specimen was dry, with the results of the 2nd loading phase (Figure 13), when the specimen was wet, just after the period of immersion in water of the specimen it can be referred that the values of deformation in the 2nd phase (wet state) are higher than the values of the 1st phase (dry state), which could allow to infer that the specimen had modified the deformation characteristics, becoming more deformable.

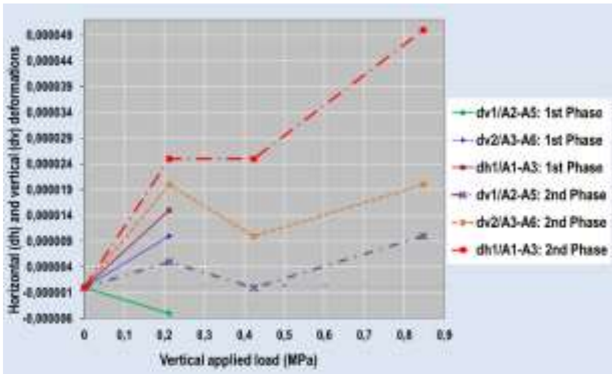

Fig. 13: Results of deformations (dh1, dv1, dv2) of the specimen M1 during 1st and 2nd loading phase, for the vertical applied load

Analyzing the results of deformations (dh1, dv1, dv2) of specimen M1, during the 2nd Phase (dry specimen), with the results of the 3rd loading phase (wet specimen) it can be denoted that the values of deformation in the 2nd phase (wet state) are higher than the values of the 3rd phase (less dry state compared to the 2nd Phase (Figure 14), due to the period of six days of drying in laboratory with controlled ambient), which could consent to suppose that the specimen had again modified their deformation characteristics, becoming less deformable in the 3rd Phase.

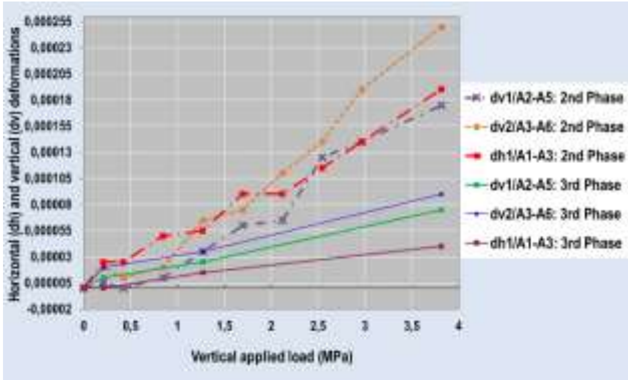

Fig. 14: Results of deformations (dh1, dv1, dv2) of the specimen M1 during 2nd and 3rd loading phase for the vertical applied load

Examining the results of mass variation/change of moisture content of Specimen M1 (drying and wetting) and measured deformations (horizontal/vertical), for 10 kN of load, in 2nd Phase (Day 2) and 3rd Phase of compression test, about the measured deformation, for 10 kN of load, in 1st Phase (Day 1), for the vertical applied load of 10 kN of load (results depicted in Table 4), it can be seen that the increase of mass of near 7.0 %, after the period of immersion (2nd Phase), corresponded to a positive variation of the value of dh1 of approximately 67,0 %, and a negative variation of the value of dv1; and in the 3rd Phase, a loss of mass of near 4.5 %, after six days of drying in laboratory with controlled ambient, corresponded to a negative variation of the value of dh1 and dv1.

Table 4. The mass variation/change of moisture content of Specimen M1 (drying and wetting) in confront to variation of the measured deformation (horizontal / vertical) for 10 kN of load, in 2nd Phase and 3rd Phase of the compression test, in relation to the measured deformation, in 1st Phase, for 10 kN of load

State of the Specimen	Variation mass relatively to the previous reading	Load (kN)	Horizontal / Vertical deformation			
			A1-A3 (dh1) / A2-A5 (dv1)	Var. (dh1 /dv1) *	A2-A4 (dh2) / A3-A6 (dv2)	Var (dh2 /dv2) *
Dry state - Day 1 (1st Phase)	0	10	0,000015 / -0,000005	-	0,000015 / 0,00001	-
After immersion (24 h) - Day 2 (2nd Phase)	0,070	10	0,000025 / 0,000005	0,67 / -2	-0,000005 / 0,00002	-1,33/ 1
Dry state after period of 6 days of drying (3rd Phase)	-0,045	10	0 / 0,00001	-1 / -3	0,000015 / 0,00002	0 / 1

* Variation of the measured deformation (horizontal/vertical), for 10 kN of load, in 2nd Phase or 3rd Phase, about the measured deformation, in 1st Phase, for 10 kN of load

Considering, the conditions that occurred in these three phases of testing, which consisted of alternating wetting and drying periods, it is probable that the bricks and the mortar joints subjected to moisture variations due to wetting and drying during these phases of testing, could have changed appreciably the hygric behavior of the specimen M1.

The impact of moisture on the mechanical response of the Specimen M1 during the three phases of testing was evident, with the change of the vertical deformations, which mean also the change of the elastic properties of the specimen due to the modification of moisture content of the specimen during the three phases of testing.

5 Moisture transfer in URM infills and influence of the interface between layers in that moisture transfer

A URM infill wall, usually, consists of several layers, which implies the moisture transport study should be based on the assessment of the conditions of continuity between the respective layers.

In reflection on the results of specimen M1, it appears that the distinction of brick units and mortar joints, without disregarding interfacial effects, could be necessary to take into account

Taking into account interface resistance and change in mortar properties, the determination of the brick–mortar interface resistance could be based on the water uptake from the bricklayer into the mortar joint, [3], therefore, the values could be determined for the liquid transport into a material with a lower absorption – compared to the first material layer. The higher retardation of the moisture transport is expected to be found in fine porous material, such as mortar joints, compared to coarser layers like brick, [3].

The liquid transport in multilayered composites and the corresponding interface resistance could be determined based on the moisture profiles [8]. Regarding moisture transport, the effect of imperfect contact interfaces in multi-layered elements (such as masonry elements) could be considered through hydraulic resistances, [6].

As referred to above (in 3.2) the characterization of material interfaces with interface resistances is a commonly used approach that could be determined by analyzing experimentally the liquid transport across the interface between masonry blocks/bricks and mortar That liquid transport across the interface could eventually change the mortar properties, and, in the case of dry-cured mortar, a higher interface resistance could be obtained, compared to the wet-cured composite, [3].

Based on the results of the measurement of deformations and of mass variations of Specimen M1 during the three phases (see Figure 15), it can be inferred that, with the rise of stresses and strains within the specimen from 1st phase to 2nd phase of the test, the hygric behavior of the specimen (porous material), possibly, had been altered, taking into account the relevance, for influencing that hygric behavior of specimen, of the moisture liquid permeability and moisture storage capacity of the bricks and the mortar joints and the interface resistance between both (Figure 16).

Probably, that the mortar of the vertical and horizontal joints of specimen M1 had a lower capillary absorption coefficient than the bricks. In addition, between brick and mortar, an imperfect contact could be possibly found. A moisture flux inside the specimen could likely have occurred from a dry state (Day 1) in the 1st Phase, passing to a wet state, after immersion (24 hours) in the 2nd Phase, and finalizing after six days of drying in a laboratory with controlled ambient, in 3rd Phase.

The interface flow was possibly significantly variable during the three phases of testing and could have been influenced by the interface position (vertical or horizontal mortar joints) and the material characteristics of the confining bricks with these interfaces.

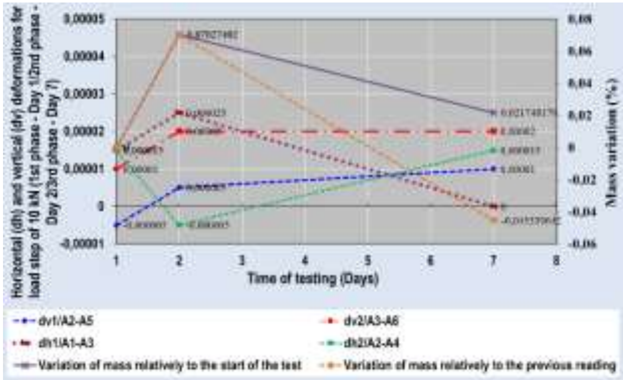

Fig. 15: Mass variation/change of moisture content of Specimen M1 (drying and wetting) and measured deformations (horizontal/vertical), for 10 kN of load, in 1st Phase (Day 1), 2nd Phase, and 3rd Phase of compression test, about the measured deformation for 10 kN of load, in 1st phase, for the vertical applied load

Fig. 16: Detail of a zone of interface between mortar joints and bricks (vertical and bed joint) in face A of the Specimen M1 at the end of 3rd Phase of the test

Moisture transport in three phases of bricks of the specimen is presumed to be different from that occurring in the interface zone of the brick-mortar joint due to the probable retardation of the liquid transport across that zone of the interface. A retarded water uptake in brick–mortar interfaces could have occurred in the Specimen M1, during the alternating wetting and drying periods of the three phases.

The brick type, the kind of mortar (joints), and the thickness of the mortar joint in the specimen M1, particularly in terms of capillarity and moisture content of the bricks and mortar, could have influenced the interface resistance and the change of the material characteristics during the three phases.

6 Assessment of hygro-mechanical coupling

Moisture transport and mechanical response in URM infill walls mutually interact, considering that mechanical characteristics of the infill masonry are changed by moisture variation and, in a reversed way, the permeability could be altered by the increase of mechanical damage. Therefore, two-way coupling between the mechanical response and the moisture transfer is possible. The development of stresses and strains within a porous material could influence the hygric responses, and the quantity of moisture adsorbed by the material may reduce, as the elements are subjected to higher compressive stresses.

6.1 Influence of moisture on the mechanical response

Concerning the influence of moisture on the mechanical response, the elastic properties and strength of the masonry could decrease due to the presence of moisture. It could be admitted that the initial response could be recovered upon drying, taking into account that the above phenomena could be considered reversible.

Considering the relation between the deformations and the vertical applied load, it could be presumed a decrease of the Young modulus with moisture content from the 2nd Phase to the 3rd Phase (Figure 17). Furthermore, the presence of moisture could presumably have modified the strength of the specimen, however, it could be admitted that this had reversible character, considering that after a period of wetting (1st phase until the beginning), in the subsequent period of 6 days of drying (3rd Phase), the initial response is partially recovered.

This specimen was subjected to high loads (almost 13 MPa of vertical pressure load) associated with values of vertical deformations which corresponded to a more compacted material, but also an upsurge of cracking. It seems probable that in the case of masonry elements (porous material), the quantity of moisture adsorbed by the material of the masonry element could be lesser if subjected to high compressive stresses. Moreover, probably the impact of high compressive stresses is higher on the sorption behavior, for elevated values of moisture content of the specimen.

Concerning the reverse coupling, which refers to the modification of moisture diffusion due to mechanical effects, it could be said that the mechanical degradation of a brittle composite material, like the masonry specimen M1, usually comprises a first phase where diffuse micro-cracking occurs and a second phase where macroscopic cracks upsurge, [12]. cracks usually could be considered to have a significant impact on transport processes, as well as on moisture diffusion, for both cases

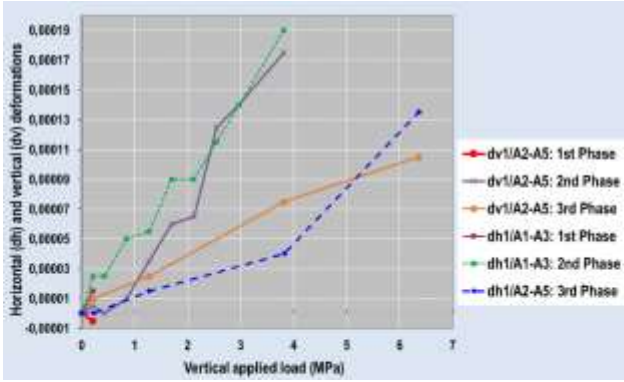

Fig. 17: Results of deformations (dv1, dh1) of the specimen M1 during the three loading phases for the applied load

6.2 Evaluation of mutual effects between moisture transfer and mechanical response

It is important to evaluate the type of interaction between the mechanical and diffusive phenomena in a coupled scenario. That could be a real situation, considering, for example, URM infill walls of RCS buildings subjected to vertical and horizontal distributed loads, and simultaneously subjected to moisture rising from the ground level, and evaporating conditions usually applied on all the external surfaces of URM infill wall of building envelope.

In terms of numerical analysis, these effects of moisture variations and mechanical response of masonry (this response could, particularly, depend on the behavior of blocks/bricks and mortar joints), could be taken into account: the degradation of the elastic properties can be included by introducing a dependence of the normal and tangential elastic stiffness coefficients, [12].

In masonry, the mortar joints can be considered as planes of weakness, regarding its evolution from the onset of cracking, until it reaches the failure caused by a certain imposed stress state due to loading. A typical Yield surface of a mortar joint is presented in Figure 18. Combinations of tension, shear, and compression failure modes can be adequately considered through a failure envelope for a masonry element, which is expressed in terms of shear strength (V_m) versus compressive stress (σ_n) (see failure envelope (V_m - σ_n), in Figure 19), [15]. The basic mechanism of a masonry element can be associated, essentially, with the following main failure modes, [15], [13], (Figure 19): shear sliding in bed joints (mode A), shear friction in the vertical and bed joints, with step formed cracks (mode B); diagonal tension of the masonry element/tensile failure of the bricks (mode C), and toe crushing/flexural tension of masonry element (mode D). The shear resistance could be conditioned by the path of the inclined oriented cracks, [15], [13]; if the cracks occur in the vertical and bed joints (step-formed cracks corresponding to friction failure of the bed joints), the resistance can be defined by the friction law, which critical parameters are cohesion (f_{vko} - initial shear strength of the masonry element (estimation under zero compressive stress) or initial interface cohesion of bed mortar joint (estimation under zero compressive stress)) and friction coefficient (friction coefficient - μ; and $\mu=\tan\phi$ - ϕ is the friction angle); the tensile strength of the masonry unit could be a critical parameter, if the cracks are across the masonry unit, [15], [13].

Tension and shear modes of failure are most common in mortar joints and brick-mortar interfaces, relative to the compression modes of failure. Properties of mortar and masonry units can influence the shear bond strength of the mortar joints to a lesser extent than the level of precompression and, depending on that level, failure can occur in the joints alone or as a combined block/brick or mortar joint failure, [13].

Aiming to take into account the decreasing strength of the masonry, the Mohr-Coulomb failure criterion can be assumed dependent on the water saturation degree, [12]. Both the cohesion and the friction angle can vary, which leads to a change in the failure criterion, as illustrated in Figure 20 and Figure 21, with the modified failure zones due to the change in the maximum tensile stress and due to the modification of the friction angle, [12].

Mechanical degradation is characterized by diffuse micro-cracking, which consents the description of the mechanical behavior through the classical damage mechanics, a commonly used approach based on taking into account the effects of the mechanical damage on the moisture diffusion process, [12].

With respect to vapor water permeability, it increases up to intermediate damage values, and then decreases for large values of damage; and a variation of vapor water permeability with the damage variable with smooth character is probable. Moreover, the liquid water permeability could presumably increase, monotonically, with the damage variable, with a more pronounced increase for low values of damage, [12].

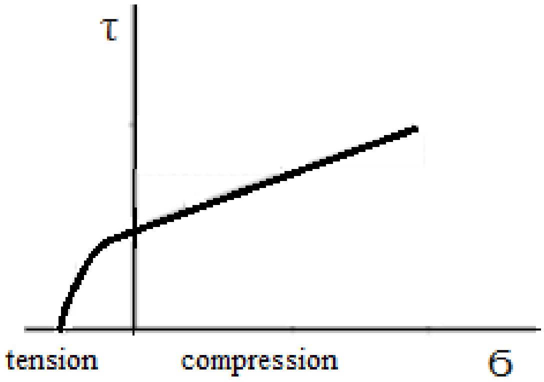

Fig. 18: Mohr failure criterion of a mortar joint (Yield surface)

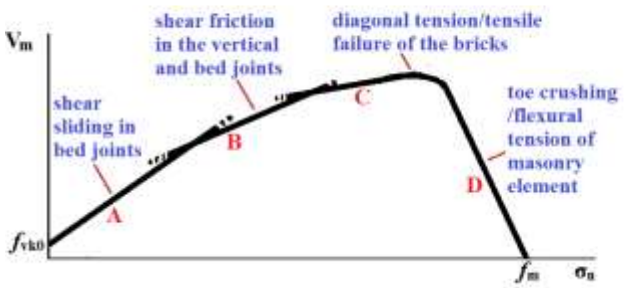

Fig. 19: Failure envelope for masonry element, [15], [13], expressed in terms of shear strength (V_m) versus compressive stress (σ_n), with four main failure modes, A to D (f_{vk0} - initial shear strength of masonry; f_m - compressive strength of the masonry)

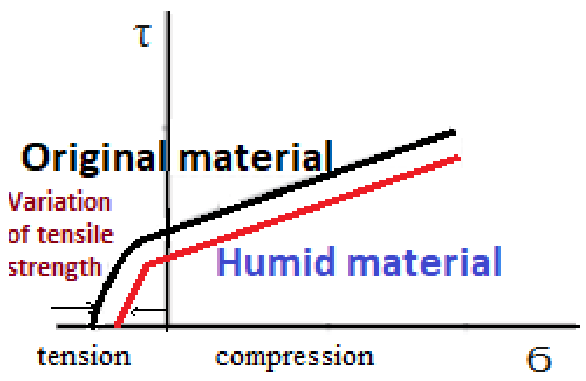

Fig. 20: Influence of degree of moisture on the Mohr failure criterion with variation of tensile strength

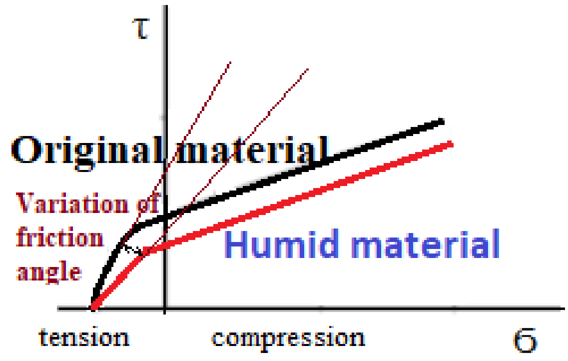

Fig. 21: Influence of degree of moisture on the Mohr failure criterion with variation of friction angle

A model that could do an explicit formulation of the dependence of the compliance, moisture capacity, and coupling coefficient on stress and liquid pressure, is supposed to be able to express the coupling between moisture and mechanical behavior, describing nonlinear moisture-dependent elasticity, stress-dependent sorption, and swelling, and moisture expel during mechanical loading, [16].

To consider the effects of the mechanical damage on the permeability it could be considered that the mechanical damage increases the effective porosity, and, as a consequence, influences the intrinsic permeability of the porous medium, [12].

7 Prevention against the causes of degradation of URM infill related to humidity and mechanical actions in RCS building envelope

RCS Buildings including unreinforced masonry (URM) infill walls can be negatively affected by anomalies in their envelope, such as cracking and water penetration, which worsen the aesthetic aspect and reduce the safety and level of comfort of those buildings. The referred degradation is due, particularly, to cracking and water penetration associated with WDR (wind-driven rain), including climate change effects on buildings. Moisture presence caused by WDR can negatively affect the durability of building facades due to the degradation of surface material and cracking.

Therefore, in the scope, of preventive and/or corrective actions along the service life of the buildings, it is convenient to have a better knowledge of the causes of humidity defects, to implement adequate maintenance and rehabilitation actions to avoid or minimize present or future humidity defects, considering that usually there is relevant contribution of humidity for the degradation of RCS building envelope. The multifaceted aspects and complexity of problems related to humidity defects in URM infill walls of RCS building envelope require the integration, in the study of these problems, of a diversity of specialties, aiming for a better understanding of the causes of the humidity-related problems in these elements and to define suitable treatments to solve these problems.

Mechanical actions could be a possible cause of humidity defects, specifically leakage defects, [17]. Associated with humidity-related defects, bio-deterioration/biological colonization and efflorescence/cryptoflorescence could be other types of defects in RCS buildings, together with rising dampness and penetration of rainwater. Rainwater is associated with the wetting of building envelopes. In wall renderings, cohesion loss/disaggregation and crumbling are directly related to the presence of rainwater. Rainwater, combined with wind, could contribute to the reduction of the cohesion process by granular disintegration, even if with light mechanical actions this kind of disaggregation, exposes aggregates and the substrate layer, [17].

The hygro-thermal and wind loads are expected to be intensified with the previewed more intense rain and increase in temperatures due to climate changes, which will accentuate the adversity of environmental conditions in terms of the impact on the durability of the construction elements of the building envelope. The risk of intensive rain driven by strong winds and/or flooding associated with the overflow of water from the ocean can particularly damage buildings envelope located in coastal areas, as a result of flood waters and inundation, with considerable negative impact on their durability, particularly of the concrete elements, [18]; and there is strong evidence of significant changes in climate during last decades, particularly in terms of the increase of mean air temperature, [18]. Furthermore, due to climate changes, besides a progressive variation of the mean values of main climate variables, like mean temperature, humidity, and sea levels, it is expected an increased frequency and intensity of extreme climate events (extreme wind-driven rain events), mainly in consequence of the global warming, which has accelerated significantly in the second half of the twentieth century, [18].

These negative previewed effects of climate change could lead to adverse situations of increased risk of aggressive degradation agents acting on the buildings, which could aggravate the processes of weathering, leading to premature degradation of construction elements of the building envelope.

That leads to the need to study more deeply the causes of humidity defects that could be related to the previewed effects of climate change, particularly considering the scenarios correspondent to assessments of projected future changes using Representative Concentration Pathways (RCPs) that can influence durability problems in buildings, [18]. More severe humid defects could be expected for the scenario of high greenhouse gas emission, about RCP 8.5, when compared to the severity of humidity defects that can be advised for the scenario of low greenhouse gas emission, Scenario A, about RCP 4.5, being the first scenario (RCP 8.5), less favorable, and supposed to lead to predictable greater intensity of rain and higher increase in temperature variations due to climate changes, relatively to that previewed for RCP 4.5 scenario.

Considering the elements of humidity defects above described, it is considered essential the study moisture migration inside the building throughout the construction elements of the building envelope, particularly through cracking of URM infill walls, [19], aiming the improve of the correspondent higro-thermal and mechanical performance, waterproofing, durability, and adequate aesthetic aspect.

8 Conclusion

Essential elements about the characteristics of moisture transfer across infill masonry (URM) and of the interface resistance with moisture flows were summarily described, and the essential evaluation of the mechanical behavior of URM infill walls when subjected to moisture variations was carried out. Moisture transport characteristics were discussed, focusing on the analyses of the behavior of masonry elements when subjected to moisture variations. An initial assessment of the mechanical behavior of URM infill walls when subjected to different moisture variations was made through a compression test of a brick masonry specimen with variable moisture content. The impact of moisture on the mechanical response of the Specimen M1 during the three phases of testing was evident, with the change of the vertical deformations, which mean also the change of the elastic properties of the specimen due to the modification of moisture content of the specimen during the three phases of testing.

Following that analysis, an evaluation was made of the moisture transfer in URM infills and the influence of the interface between layers in that moisture transfer, particularly considering the results of the test of Specimen M1. Subsequently, an assessment is made of hygro-mechanical couplings.

Finally, elements for prevention about the causes of degradation of URM infill related to humidity and mechanical actions in the RCS building envelope were discussed.

Some of the limitations in this study could be related, especially, to the lack of deep evaluation of the effect of variation of moisture content of the masonry specimen on the deformability and the strength of the masonry element, particularly in the phase of high loads in the compression test.

Regarding the contributions of this work to previous works in literature, a comprehensive analysis of mutual effects between moisture transfer and mechanical response in infill masonry walls in reinforced concrete buildings is considered to have been suitably made in this paper, through an assessment of the mechanical behavior of URM infill walls, when subjected to different moisture variations, especially based on the analysis of a compression test of a brick masonry specimen with variable moisture content, with positive repercussions in terms of their better knowledge. That knowledge could be useful, in terms of the practical applicability for the assessment of the moisture transfer in URM infills and the influence of the interface between layers in that moisture transfer.

In terms of benefits of the proposed analysis, it is admitted that the present paper has successfully highlighted an essential characteristic of URM infill walls behavior related to the mutual effect between moisture transfer and mechanical response, and can provide, for future scientific research work, a helpful reference for hygro-mechanical couplings, considering the contribution of the paper for the assessment of mechanical behavior of URM infill walls when subjected to different moisture variations and varying vertical loads, which was made through a compression test of a brick masonry specimen with variable moisture content.

As possible future developments, improvements, and future directions of this work, it is recommendable that should be further studied, deeply, the hygro-thermal-mechanical behavior of URM infill walls, aiming, in particular, to better understand the impact of moisture on the mechanical behavior of URM infill walls, particularly by deepening the evaluation of the effect of variation of moisture content of masonry elements on the deformability and the strength of the masonry element, taking into account linear and non-linear behavior and damage, as well as the reverse coupling, which means the mechanical effects (stress variation, volumetric changes, cracking and damage) on moisture transfer. Besides, a better knowledge of the relationship between the heat and moisture fields and solid mechanics could be pursued, considering, in particular, the influence of hygro-thermal and wind loads on the mechanical performance of URM infill walls.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

José Dias had the ideas and was responsible for formulation of overarching research goals and aims of this paper;

José Dias was responsible for conducting the research and for the development of the methodology of the study;

José Dias has organized the experiments referred in the section 4, and was responsible for their execution;

José Dias carried out the preparation, creation of the published work.

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Conflict of Interest

The author has no conflict of interest to declare that is relevant to the content of this article.
