LABORATORY INVESTIGATION OF DAMP RISE IN POROUS MASONRY CONSTRUCTION MATERIALS

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ABSTRACT

A laboratory work has been initiated within the framework of a 7°FP European project, (SMooHS) aimed at monitoring and evaluating the evolution of environmental degradation in historical structures and its consequences. One of the major causes of decay in masonry is moisture and salt capillary rise in the materials, thus, a better comprehension of the damp rise phenomenon in masonry walls and of salt crystallization is necessary. In order to achieve this aim, the hygrothermal properties of both the constituent materials and the masonry considered as a whole, have to be known. The few available standards related with these phenomena are concerned with the behaviour of single units of building materials in contact with water and allow the determination of parameters such as the water absorption coefficient. Testing standards considering masonry assemblies or regarding the mechanical effects of salt rise in construction materials do not exist. Consequently, an experimental work has become necessary to satisfy the research requirements.

Several absorption tests have been conducted in the laboratory, in a controlled environment, on brick units, mortar samples and simple masonry assemblies by using water or aggressive agents’ solutions (sodium chloride brine at different concentrations). In this paper, preliminary results of the on-going experimental research are reported comparing the values of the suction velocities determined for the different brines rising in single materials with the values obtained for small masonry specimens. These parameters are interesting from different points of view, as they can be used to understand possible changes in the masonry diffusivity, to create a data bank which does not exist in these terms or as input values for numerical simulations aimed at properly modelling the diffusion processes in porous materials.

Keywords: Masonry, damp rise, experimental, testing standards

1. RESEARCH REQUIREMENTS AND REVIEW OF RELATED NORMS

The mechanisms responsible for the deterioration of porous building materials are strictly related with moisture transport and salt capillary rise phenomena. They represented a topic of continuous research since the 1960’s [1-3] because of their complexity, as they involve a large number of parameters usually inter-connected, and because of their economic implications. Much has already been done with this respect but much has to be done. As an example, there is still a strong interest in finding reliable and repeatable ways of determining the macroscopic hydraulic properties of porous media as stated by different authors [4-5]. In order to achieve this aim and obtain a detailed knowledge about the damp rise and the diffusivity mechanisms in masonry, the characteristic hygrothermal properties of the single building construction materials, such as brick units and mortar samples, as well as the properties of masonry assemblies have to be known. This information would be important both from an experimental view point as it would allow a deeper understanding of the degradation processes, helping in finding proper methods for diagnosis and for appropriate treatment solutions, and from a numerical point of view in order to assess and calibrate ad-hoc models able to i.e. estimate the evolution of the decay mechanisms in historical masonry.

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At this regard, few international testing standards are available and they are concerned with the behaviour of single masonry constituent materials in contact with water. As a matter of fact, the dangerousness of the presence of water in a structure, which may cause modifications or decay in the materials, has been recognized from International Technical Committees and, i.e. it has been found that an increase in the value of the water absorption coefficient can be related to an alteration process [6]. Thus, the norms mainly describe water absorption tests to be performed on sets of small samples (typically 3 or 6 cubes with 50 mm side) of hardened mortars [7, 8], natural stones [9, 10] and, not well specified specimens of porous inorganic materials used for and constituting cultural properties [11]. In detail, for both mortars and natural stones, the laboratory tests consist in positioning a specimen, previously dried to constant mass, into an uptake container with a constant level of tap water at room temperature (and atmospheric pressure) and in measuring its weight at different time periods (according to the type of material or the speed of water absorption) until constant mass. Thus, the water absorption coefficient can be determined. This parameter is defined as the amount of water absorbed per unit area (expressed in grams/cm²) as a function of time from a sample with one surface in contact with deionised or tap water [11, 12] or as percentage obtained by the ratio of the mass of the saturated sample to the mass of the dry specimen [9].

A slight difference has been found in [11] as this European Standard specifies a method, that may be applied to porous inorganic materials (either untreated or subjected to treatment or ageing) to determine both the amount and the rate at which a specimen absorbs water by capillarity through a surface in contact with water. Thus, it allows the evaluation of the water absorption coefficient as well as of the capillary water penetration coefficient, defined as “the slope of the curve obtained reporting the height of the water front migration versus the square root of time, calculated by linear regression”.

The behaviour of assemblies of 2 or more construction materials (i.e. brick masonry) in contact with water is not considered at all in the norms. In addition, the effects of dissolved salts within porous media has not yet been included in these types of tests. The only references to salts are to be found in the few standards available in the field of accelerated ageing tests of materials [13-15], which, anyhow, refer to very small specimens of stones, marbles or brick units and do not really explain the relationship between the obtainable results in the case of accelerated ageing and the ones to be achieved by natural environmental ageing. Consequently, the conducted experimental investigations aimed to investigate some of these research requirements.

2. WORK AIMS

An experimental work aimed at investigating the damp rise phenomenon in masonry and at determining the diffusive properties of both the constituent materials and the masonry considered as a whole has been carried out in order to satisfy some of the research requirements raised within the framework of the 7th FP European project SMooHS. Given that the standard procedures above reviewed do not fulfil the research demands (i.e. determining the differences in the masonry capillarity in presence of water or salt solutions rise), several ad-hoc designed absorption tests have been conducted. The laboratory investigations have considered brick units, mortar samples and simple masonry assemblies in different environmental conditions (i.e. controlled environment into a climatic chamber or monitored laboratory conditions), subjected to water or aggressive agent’s solutions rise and have also taken into account the evaporation’s effects.

In this work, preliminary results of the on-going research are presented comparing the values of suction velocities and capillary suction coefficients obtained for the different brines rising in single materials with the values determined in masonry specimens.

3. MATERIALS AND METHODS/EXPERIMENTAL WORK

3.1. Description of the specimens

Commercially available solid brick units of UNI standard dimensions 25 × 12 × 5.5 cm³ have been tested in the laboratory facilities of the DICAM Dept., Bologna University, Italy, together with natural hydraulic lime mortar prisms of dimensions 4 × 4 × 16 cm³. These building materials have been chosen because they were the component materials of various large masonry specimens, designed and built in Bologna in the same research project to simulate historic constructions, subjected to natural environmental decay [16-18]. The material’s physical properties relevant to the capillary water transport.
phenomena, such as the density, the porosity and the pore size distribution are known as they have been preliminarily determined in the MPA laboratory of Stuttgart University within the frame of the EU project [19]. Some small masonry assemblies, made of the same constituent materials, have also been tested. In this paper, only one 6-brick column, with 1cm-thick mortar joints will be considered. The specimen (dimensions $b \times s \times h$ equal to $25 \times 12 \times 38$ cm$^3$, Fig. 1) presented three of the four lateral faces coated by a waterproof layer in order to limit the evaporation rate. The small masonry specimens as well as some of the tested brick units and mortar samples were instrumented by embedding electrical potential and internal temperature sensors. The potential sensors are sensitive to the concentration of sodium chloride solution in the materials and were developed and provided by courtesy of MPA researchers. The effects of the sensors’ holes and presence on the hydric parameters of the porous materials are not taken into account in this paper and they will be presented, together with the data collected by the wireless monitoring system in a further work. However, it is necessary to mention this aspect as the presence of the sensors and their cables has influenced/conditioned the set-up choice of this experimental work.

![Fig. 1 A red brick unit (a) and a mortar prism (b) at the beginning of the absorption experiment; geometrical dimensions of the 6-brick masonry column (c).](image)

### 3.2. Test procedures

#### 3.2.1. Absorption tests on the masonry constituent materials

The absorption tests on brick units and mortar prisms were conducted in one of the climatic chambers of the LISG laboratory in Bologna that means in a controlled environment characterized by constant values of air temperature and air relative humidity, respectively $20^\circ\text{C}$ and 60%. This was aimed to restrict the effects of the boundary conditions on the diffusivity properties. The specimens were weighted at the beginning of the tests obtaining a reference value useful to determine the amount of brine and water vapour from the air absorbed during the test. In addition, one brick unit (1B5) and one mortar specimen (1M5) have been previously dried to constant mass according to [11].

After marking a graduated 5-mm scale by pencil on one or more faces of each sample these were placed vertically into a tray containing a layer of cotton wool. This layer was soaked by distilled water or salt brine before placing the sample on it. The brines were at different concentrations, according to testing aims. The details of the test set-up are reported for the brick specimens and for the mortar prisms, respectively in Table 1 and Table 2. The level of brine has been kept constant (about 3mm in height) during the capillary rise test (Fig. 1b).

### Table 1 Series of brick units for absorption tests

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Solution used for the rise damp test</th>
<th>Installed sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B1</td>
<td>distilled water</td>
<td>No</td>
</tr>
<tr>
<td>1B2</td>
<td>NaCl 30%wt</td>
<td>Yes</td>
</tr>
<tr>
<td>1B3</td>
<td>NaCl 10%wt</td>
<td>Yes</td>
</tr>
<tr>
<td>1B4</td>
<td>NaCl 30%wt</td>
<td>No</td>
</tr>
<tr>
<td>1B5*</td>
<td>distilled water</td>
<td>No</td>
</tr>
</tbody>
</table>

* previously dried in oven to constant weight
### Table 2 Absorption tests on mortar prisms

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Solution used for the rise damp test</th>
<th>Installed sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1M1</td>
<td>Distilled. Water</td>
<td>No</td>
</tr>
<tr>
<td>1M2</td>
<td>NaCl 30%wt</td>
<td>Yes</td>
</tr>
<tr>
<td>1M3</td>
<td>NaCl 10%wt</td>
<td>Yes</td>
</tr>
<tr>
<td>1M4</td>
<td>NaCl 30%wt</td>
<td>No</td>
</tr>
<tr>
<td>1M5*</td>
<td>Distilled water</td>
<td>No</td>
</tr>
</tbody>
</table>

* previously dried in oven to constant weight

The rising damp level on the sample was visually monitored and measured at defined time intervals (about every minute in the first hour of testing and every 15 minutes until the end of the test. The test was stopped at the time when the sample top face appeared completely wet. In fact, due to the presence of the monitoring sensors and cables it was not possible to weight the samples at repeated intervals up to constant weight) by using a roll meter on the 4 faces of the samples. Photos were also captured by a digital camera at the same time intervals.

The temperature of the specimen’s surface was repeatedly measured at different positions (in wet and dried areas) and the temperature of brine has also been monitored with a portable termohygrometer. Given that in many cases it was not possible to measure the weights variations of the specimens during the tests, as suggested by the available standard procedures, because of the uncertainty due to the presence of the cables of the inserted sensors, the results are presented, according to [11] reporting the visible height of the water front migration versus the square root of time. The specimens have been weighted at the end of the experiments in order to obtain an estimation of the amount of brine absorbed.

#### 3.2.2. Absorption test on a six-brick masonry columns

In order to evaluate the influence of salts on the suction velocity of brick masonry, one small masonry assembly (S1) was subjected to a rising damp experiment similar to the ones described in the previous section for the constituent materials’ units (§3.2) (Fig. 2).

The main differences in the testing procedure were the climatic conditions and the brine used (Table 3). This experiment was conducted in a quiet laboratory room, in a monitored but not-controlled environment, using a low concentrated (0.1% -wt.) sodium chloride solution. The environmental parameters were monitored by a termohygrograph, the air temperature was almost constant, around 22°C while the relative humidity ranging daily from 30% to 60%.

### Table 3 Masonry specimen: test set-up

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Solution used for the rise damp test</th>
<th>Installed sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>NaCl 0.1% wt</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Fig. 2 Phases of the brine capillary rise on the 6-brick column: 6.30h (a) and 29 days after the beginning of the test (b)

Due to the waterproof coating on the other lateral faces, the capillary rise level was visually monitored and measured with a roll meter only on the front surface of the specimen (not sealed) while it was not possible to weight the specimen at different steps due to the presence of sensors cabling.
In order to observe in detail the variation of the visible moist front on this surface, three different vertical sections have been monitored: one near the right edge, one near the left edge and one, in the centre of the surface, near the measurement scale drawn by pencil. Thus, the possible different behaviour of the damp rise near the edges of the specimen has been taken into account.

The visible rise heights were collected approximately each 5 minutes in the 1st hour of the experiment, each 10 minutes in the first day and each 30 minutes/1 hour until the end of the experiment that lasted 35 days. As the presence of an operator was necessary to monitor the experiment, data have been recorded only in weekdays during working hours.

Also in this case, the absorption curve was visualized in terms of variations in time of the moist level. In addition, when possible, the surface temperatures of the wet and dry bricks have been collected by a portable termohygrometer.

4. RESULTS AND DISCUSSION

4.1. Masonry constituent materials: absorption tests

4.1.1. Brick units

The absorption tests on each brick unit lasted between 49 and 64 hours, according to the concentration of the brine used. The rising damp levels (in cm) measured at regular time intervals have been visualized as a function of the square root of time (expressed in hours) for each specimen (Fig. 3). The slope of the absorption curve denotes the suction velocity (expressed in cm/h^{0.5}), a parameter characterizing the absorption behaviour of the materials. As the 5 brick units tested were from the same batch it is reasonable to expect that they are characterized by the same (or very similar) physical properties, and as the same testing procedure was followed, the brine results to be the only varied parameter (not considering the presence of sensors).

Thus, the suction velocity varied with the used solution and decreased in an inversely proportional manner with the salinity of the solution itself. In detail, the highest values of suction velocity have been determined for the two samples tested with distilled water (1B1 and 1B5) and the lowest for samples 1B4 and 1B5, tested with the highest sodium chloride solution (30% -wt) (Table 4). This occurs because the presence of dissolved salts tends to occlude the micro-pores and to slow the moisture rise within the material, as demonstrated by several works [18-20].

![Fig. 3 Results of suction tests on brick units performed with water or different brines: height of rising damp (cm) vs. SQRT of time (h^{0.5})](image)

The values of velocity obtained for specimens 1B1 and 1B5, both tested with distilled water, are slightly different according to their different initial boundary conditions. The first one (1B1) was placed in the climatic cell, before the test, until reaching the constant weight (equilibrium with the environment) while the second unit (1B5) had been previously dried to constant weight in an oven. It was observed that the presence of a certain amount of moisture within the specimen eases and “accelerates” the water absorption process; even so, the two samples have gained almost the same weight (443.6 g and 445.7 g).
The capillary suction rate has been estimated for the tested bricks using as input the measured porosity of 23.2\% (upper limit for the water-accessible pore space) and the estimated solution density extracted from available data banks (Table 4). This parameter is proportional to the suction velocity but small discrepancies could be due to the fact that not the whole pore spaces are accessible to water.

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Starting Weight [g]</th>
<th>Final Weight [g]</th>
<th>Duration [hours]</th>
<th>Suction velocity [cm/h1/2]</th>
<th>Capillary suction rate [kg/m2h1/2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B1</td>
<td>2876</td>
<td>3319.6</td>
<td>168**</td>
<td>3.22</td>
<td>7.47</td>
</tr>
<tr>
<td>1B2</td>
<td>2861.9</td>
<td>3458.1</td>
<td>168**</td>
<td>2.85</td>
<td>7.86</td>
</tr>
<tr>
<td>1B3</td>
<td>2933.2</td>
<td>3352.5</td>
<td>69,5</td>
<td>3.14</td>
<td>7.82</td>
</tr>
<tr>
<td>1B4</td>
<td>2928.5</td>
<td>3486.4</td>
<td>168**</td>
<td>2.69</td>
<td>7.42</td>
</tr>
<tr>
<td>1B5</td>
<td>2883.5</td>
<td>3329.2</td>
<td>94</td>
<td>3.25</td>
<td>7.54</td>
</tr>
</tbody>
</table>

** this value corresponds to the time at which the operator saw the end of the test and stopped it, it is not the real duration.

4.1.2. Mortar prisms

The absorption experiments of the mortar prisms lasted approximately 6 hours for specimen 1M1 (the fastest one) and over 10 hours in specimen 1M4 (the slowest one). Also in this case, the results are presented in terms of visible damp level (in cm) vs. square root of time (in hours) (Fig. 4). These visual surveys confirm a reduction in the suction velocity with the increase of the brine concentrations.

![Rising damp on unsealed mortar samples](image)

**Fig. 4** Height of rising damp vs. SQRT of time in lime mortar samples monitored by visual inspection, comparison between several solutions.

The capillary suction rate has been determined only for samples 1M1 and 1M2, considering the measured porosity of 20.6\%, representing these the two extreme cases respectively with distilled water and NaCl 30\% -wt. The value obtained in the 2\textsuperscript{nd} case is almost 15\% lower than the one of the 1\textsuperscript{st} case (Table 5).

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Duration [hours]</th>
<th>Suction velocity [cm/h1/2]</th>
<th>Capillary suction rate [kg/m2h1/2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1M1</td>
<td>6</td>
<td>6.70</td>
<td>14.31</td>
</tr>
<tr>
<td>1M2</td>
<td>24**</td>
<td>5.00</td>
<td>12.22</td>
</tr>
<tr>
<td>1M3</td>
<td>11</td>
<td>5.28</td>
<td>-</td>
</tr>
<tr>
<td>1M4</td>
<td>24**</td>
<td>5.03</td>
<td>-</td>
</tr>
<tr>
<td>1M5</td>
<td>70**</td>
<td>6.56</td>
<td>-</td>
</tr>
</tbody>
</table>

** this value corresponds to the time at which the operator saw the end of the test and stopped it, it is not the real duration.
Comparing the results obtained for the two constituent materials tested, interesting observations can be drawn. The suction velocity determined for the mortar samples was almost 1.6 times higher than for the brick units tested in the same conditions. An explication could be that although the red bricks are characterized by higher porosity, they present a sharp and narrower range of pore size distribution than the mortars. This decreases the velocity. This aspect is evident for all the tested brines (distilled water and different sodium chloride solutions). Nonetheless, it is important to highlight that, due to the statistical spread in the samples porosity some limited differences in the behaviour of mortar prisms (i.e. mortar samples 1M1 and 1M5 if compared with brick units 1B1 and 1B5) contaminated by various solutions may be overshadowed by the discrepancies in porosity values of the used samples.

4.2. Simple masonry assembly: absorption test

The absorption test in the small masonry specimen lasted 35 days. The average value of the measured capillary rise levels vs. square root of time for the six-brick column shows that the calculated suction velocity for the entire duration of the test was found to be 1.6105 cm/h^{1/2}. The moisture height considered was the average of the 3 values measured on the specimen’s front surface; the values measured near the edges, in fact, were slightly different (greater) than the one recorded in the central section of the front surface, due to the proximity of the edges to the waterproofed faces of the specimen where avoiding evaporation affects the damp rise.

From Fig. 5, the suction velocity seems not linear and it is quite fast in the early test hours (in the 1st hour of test, a value of 3.4 cm/h^{1/2} has been measured) then, as the hours pass, the slope of the curve decreases as does the suction velocity (value referred to the 1st day: 0.48 cm/h^{1/2}). Other clear changes in the damp rise speed have been noted after two days and after a week from the beginning of the experiment. In order to evaluate and highlight the influences of the interfaces in the capillary rise test, red horizontal lines have been added into the graph to indicate the position of the 5 mortar joints (Fig. 5). In proximity of the mortar joints, when the brine front has reached the brick/mortar and mortar/brick interfaces and the operator was present to monitor the rise level, the curve on-going has shown decreases in suction velocity followed by sudden increase in velocity.

![Graph of capillary rise level vs. square root of time](image)

**Fig. 5** Height of rising damp (mm) vs. SQRT of time (h0.5) monitored by visual inspection, red lines represents the location of mortar joints

From this preliminary test of capillary rise in a small masonry assembly, some important considerations can be highlighted. The suction velocity calculated herein, equal to 1.6 cm/h^{0.5} is lower than the values obtained from the component materials if tested in these particular conditions. By a linear approximation, for the mortar the expected velocity value would almost be equal to 6 cm/h^{0.5} while almost 3.2 cm/h^{0.5} for the red brick. This high reduction in the diffusion properties of the masonry may be explained by the presence of the mortar joint interfaces where the solution has to fill the macro-pores between brick and mortar joints before continue rising.
5. CONCLUSIONS

Preliminary results of an extended experimental parametric study on the hydraulic behaviour of porous construction materials have been presented within the framework of a 7°FP European project aimed at obtaining a better comprehension of the damp rise phenomenon in masonry constructions and of the related decay.

Several absorption tests have been carried out in different climatic conditions on single units of building materials and on a masonry specimen, considering distilled water or salt solutions at different concentrations. The outcome of the capillary rise tests has been shown in term of suction velocity and capillary suction rate demonstrating that the suction velocity varies with the solution used, decreasing in an inversely proportional manner with the salinity. This is true both for the brick units and for the hydraulic lime mortar prisms. It occurred because the presence of dissolved salts tends to occlude the micro-pores and to slow the moisture rise within the material.

The suction velocity measured for mortar was almost 1.6 times higher than for brick, which is characterized by higher porosity but presents a sharp and narrower range of pore size distribution than the mortar.

Instead, the average velocity value of the measured capillary rise level for the six-brick masonry column is lower than those estimated for the single component materials. This behaviour can be explained by the presence of the mortar joints: when the solution reaches an interface it has to fill the macro pores between brick and the mortar before continue rising. This is visible in the curve on-going as a decrease in suction velocity followed by a sudden increase.

The experiments have helped the researchers to understand changes in masonry diffusivity; further they may be used to create a data bank for building materials that does not exist in these terms. In addition, the obtained values were used as input in a detailed calibration of numerical models aimed at replicating the diffusion processes in porous materials and at predicting the physical and mechanical damage processes in historic brick masonry.

Further experiments are planned considering the evaporation effects on the single units and the diffusivities changes in masonry assemblies when different types and concentrations of brine are used.

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REFERENCES