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RESEARCH ARTICLE

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A new sensorized ceramic plug for the remote monitoring of moisture in historic masonry walls: First results from laboratory and onsite testing

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Abstract

The presence of moisture in historic buildings, especially from rising damp, is extremely widespread and severe, causing materials' deterioration, internal discomfort and bad thermal insulation of external walls. Although this phenomenon is widely studied in the literature, the available solutions are frequently only partially effective, also due to the lack of reliable and compatible techniques to monitor the amount of moisture inside porous building materials, especially in heritage buildings where multiple restrictions exist.

In this paper, a new sensorized ceramic plug was developed, to be inserted in historic masonry walls for the remote monitoring of moisture. The plug includes a moisture sensor that is currently used for soil irrigation purpose in agriculture and a ceramic envelope of tailored properties. The plug was developed in laboratory following a step-by-step testing program, which took into account both the specific features of the sensor (requiring a strong research effort to be transferred to building materials) and those of historic walls. After a first set of laboratory tests, the sensorized ceramic plug was validated in small-scale laboratory walls and in a real historic masonry in the monumental Certosa cemetery in Bologna, Italy. The results are extremely encouraging, as they show how the new plug can provide valuable information about the rising damp evolution, and in fact, the data were correlated with the changes in the concurrent environmental parameters in the area of the cemetery. The results also suggest some possible measures to improve the sensorized ceramic plug in the near future.

KEYWORDS

brick, cultural heritage, gravimetry, mortars, rising damp, sensors, validation

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1 | INTRODUCTION

Meeting the ever-increasing needs of environmental sustainability, energy saving and people's well-being in buildings requires a strong innovation in materials, technologies and processes. This goal is particularly challenging in old, historic and heritage buildings, which represent a large part of the building stock in many countries[1] and which may be affected by several problems of bad thermal insulation, uncomfortable indoor conditions and materials' deterioration. In this scenario and especially in heritage buildings, it is very important to carry out not only recovery and restoration interventions, but also a monitoring of the materials' state, aiming at the prevention of damage by timing maintenance works.[2–4] In particular, the presence of moisture (liquid water) is one of the most damaging factors for materials, both in new and historical buildings[5] and it deserves monitoring.[6] The presence of water inside masonry walls dramatically affects their thermal insulation, also worsening the health conditions of people inside the building.[7] Furthermore, building materials, such as bricks, plasters, mortars and natural stones, if wet, are more easily subject to salt crystallization problems, frost damage, biological growth on the surface, chemical attack due to reactions with aggressive compounds present in the air (e.g., pollution).[8–12] Finally, the presence of moisture in porous building materials may affect their mechanical strength[13–15] and jeopardize the effectiveness of some strengthening solutions.[16–18]

Any repair or restoration intervention aimed at solving these problems at the root should start from a good knowledge of the state of the building materials and the deterioration causes.[11] Otherwise, the solutions adopted will be only temporary and the problems related to moisture will appear again after short time. For this goal, measuring in a quantitative way the moisture amount in masonry walls (especially those affected by rising damp from the ground) is fundamental for any restoration intervention,[5] being necessary:

- to detect the actual origin of water;
- to select the most suitable technique to reduce or possibly eliminate moisture from building materials;
- to assess the effectiveness of the repair works after some months, thus also taking precautions against possible ineffective systems proposed in the market; and
- (in the case of remote monitoring) to receive a warning in case of unexpectedly high moisture level, allowing to carry out timely inspections and repair.

However, determining moisture in a reliable way is not easy.[19,20] The direct measurement of moisture by gravimetry[20] is accurate and reliable, but it requires that samples are collected and analysed in laboratory. Destructive techniques cannot be easily applied in buildings having historic or artistic values, especially when the monitoring campaign must be protracted over time.[12,21] Hence, many non-destructive techniques were developed in the last decades,[8,10,11,21] based on the use of sensors and probes that perform indirect moisture measurements, meaning that they measure parameters that are influenced by the amount of moisture in the material. The most popular techniques are those based on electrical properties such as resistance, impedance, capacitance and dielectric constant, and time-domain reflectometry (TDR), evanescent-field dielectrometry (EFD) and techniques based on microwaves and radar waves.[8,11,12,21–28] Thermal properties are also exploited for the determination of moisture in materials, for example, by inserting thermocouples in selected points of the masonry or by using optical fibres for a distributed measurement along their entire length.[8,11,29–32] Infrared thermography can be used too, as wet materials are usually cooler that dry ones due to the occurrence of water evaporation, but it provides only qualitative data.[8,11,12,22] Widely used, especially in the agricultural field, are the techniques based on 'proxy' materials, that is, elements of wood, plaster or porous media inserted into the soil or a masonry and brought into thermo-hygrometric balance with the surrounding material.[11,25,33] Finally, there are experimental techniques mainly used for research purposes, based on the use of radiations, gamma rays, X-rays and neutron scattering, whose delicate and expensive instruments are hardly suitable for in situ use.[8,10,11]

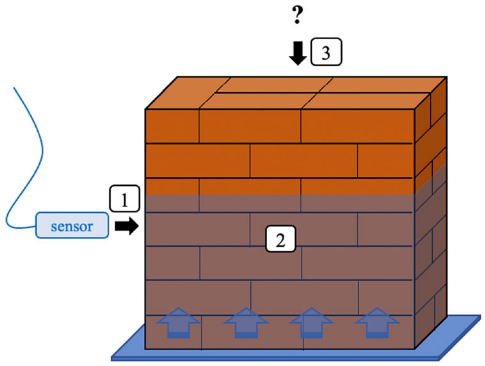
The indirect techniques for moisture content determination are many, but the measured parameters never depend solely on the water content of the material. Each method and each sensor/probe are affected by different variables, which should be considered to obtain reliable results. The contact between the material's surface and the probe (depending on surface roughness), the presence of metal elements, the presence of salts, the frequency in electrical techniques and the climatic conditions in infrared thermography are just some examples of the variables that should be considered.[8,10,21] Moreover, it should be essential to carry out an accurate calibration of the selected method in the material/masonry to be analysed, but even in this case, the procedure is very complex. In the case of historic masonry, the natural heterogeneity of pre-industrial bricks should be considered[12]; hence, a brick-by-brick calibration would theoretically be necessary, which is obviously impossible in real practice. Moreover, historic masonry is often the result of an overlapping of structures built or modified (whole or in part) in different periods; hence, it often happens that bricks of different sizes, made from different raw materials and fired at different temperature are present side-by-side in the same masonry.

2 | RATIONALE AND AIM OF THE RESEARCH

In this study, a new solution was developed for the remote and quantitative monitoring of moisture in masonry walls, consisting in a sensorized ceramic material to be inserted as a 'plug' in the wall. The idea of manufacturing a sensorized ceramic to monitor historic walls was proposed also elsewhere,[34] but for a completely different purpose, namely, to detect variations in mechanical stresses or strains in masonry walls. Here, a sensorized ceramic plug was developed to measure the moisture amount in masonry, possibly also providing a warning in case of critical situations, avoiding further damage to masonry. In this study, laboratory walls were used for the development and validation of the new sensorized solutions. Three main challenges were identified in the research, as shown in Figure 1.

These three challenges were coped with as in the following:

1. The sensor is not directly inserted in the masonry wall, because it would be impossible to calibrate it, given the unknown and heterogeneous nature of the bricks. To overcome this problem, the sensor was embedded in a ceramic material, that is, a brick of known characteristics. The sensor and the ceramic material jointly constitute the 'sensorized ceramic plug' to be inserted in the wall. The sensor was calibrated for the ceramic envelope in which it is inserted, while the relationship between the amount of moisture in the ceramic envelope and the amount of moisture in the real wall was investigated separately in this study.
2. Reproducing rising damp in a small-scale wall built in laboratory requires that an ascending capillary flow of water is established and that the amount of moisture decreases with height, as in real walls. In principle, manufacturing small walls and subjecting them to capillary water rise is easy, as they can be simply put in contact with water at the base. However, there are some practical problems. If the walls are manufactured with highly porous mortar joints (e.g., lime-based), they will quickly become fully saturated and the same moisture amount will be present everywhere in the wall, making any measurement with sensors quite trivial. If mortar joints having low porosity are used (e.g., cement-based), the risk is a very limited height of water rise, making the wall basically useless. To overcome this problem, different joint mortars were investigated in this study, aiming at slowing down the capillary water flow without completely blocking it.



1. how can the sensor be calibrated, considering that the bricks in any old masonry are heterogeneous and unknown?
2. how can rising damp be reproduced in laboratory?
3. which independent method can be used to measure moisture, for the validation of the sensor?

FIGURE 1 Three major challenges involved in the development of sensors and their testing in small-scale masonry specimens in laboratory

3. Concerning the independent technique for moisture measurement, a technique based on the gravimetric method was selected. This technique is based on the use of ‘permanent sampling points’ and was developed by the authors.[12]

This study was carried out in the frame of the MImeSIS project (Materiali Smart Sensorizzati e Sostenibili per il Costruito Storico [Sensorized and sustainable smart materials for historic buildings]), funded by Emilia-Romagna Region in Italy.[35] MImeSIS was aimed at developing a range of sensorized materials able to remotely measure specific parameters indicating the ‘state of health’ of masonry and applying them to some pilot buildings.

3 | MATERIALS AND METHODS

3.1 | Bricks

During the experimental tests, four different kinds of commercial solid fired-clay bricks having common size ~25 × 12 × 5.5 cm^3 were used, here named BRICKS 1–4. Their main characteristics were determined on three replicates for each brick, according to EN 15801:2009[36] and EN 772-13:2000,[37] and the relevant results are reported in Table 1.

3.2 | Design of the sensorized ceramic plug

An accurate survey was firstly carried out in the market, to find a type of sensor potentially exploitable for the measurement of moisture (liquid water amount) in masonry. Two sensors were selected, which are currently used for monitoring purposes in a completely different field, that is, agriculture. The first one is a sensor for moisture measurement in the soil (Watermark Soil Moisture Sensor, Irrometer, USA), while the second one is a probe for temperature measurement in the soil (PT1000, Libelium, Spain). A maximum of three Watermark sensors and one PT-1000 temperature probe can be connected by cables to a control and transmission data unit (Plug & Sense! Smart Agriculture Pro Wi-Fi, Libelium, Spain). Through Wi-Fi network, the control unit uploads the measured values to a cloud in real time, where they can be accessed in the form of table or graph.

The moisture sensing probe consists of two electrodes highly resistant to corrosion embedded in a granular matrix below a gypsum wafer. The resistance value of the sensor is proportional to the soil water tension (SWT, in cbar), a parameter depending on moisture that reflects the pressure needed by the roots of plants to extract the water from the ground, hence providing an indication about the need of irrigation.[38,39] The Watermark sensor was developed and launched in the market in 1978[40] for the agricultural sector, where it diffused as a support to more efficient cultivation systems from the point of view of water consumption, as it provides information on the soil irrigation need. Robustness and low sensitivity to salts are some major advantages of this sensor. Although there is not a specified lifetime for this sensor in the datasheet by the manufacturer, tests were carried out in the MImeSIS project, demonstrating the resistance of the sensors to simulated aggressive environments in laboratory (freeze–thaw cycles, high salts concentration, wetting-drying cycles and heat/rain cycles).[35] Examples of sensorized systems including this type of sensing probe and their applications in agriculture are reported in the scientific literature,[41–46] while no examples of their use in different fields were found, to the authors' best knowledge. The soil temperature sensor probe complements the monitoring of the soil conditions.

TABLE 1 Characteristics of the bricks used in the tests

Name	Bulk density (kg/m^3)	Water absorption at saturation (wt%)	Capillary water absorption coefficient, AC ($kg/m^2\sqrt{s}$)
BRICK 1	1591 ± 5	19.29 ± 0.03	0.1920 ± 0.0204
BRICK 2	1756 ± 11	16.44 ± 0.12	0.1557 ± 0.0146
BRICK 3	1596 ± 2	19.23 ± 0.18	0.2302 ± 0.0124
BRICK 4	1331 ± 24	28.33 ± 1.27	0.2871 ± 0.0076

No application of these sensors to building materials seems to have been carried out so far, to the authors' best knowledge, although a similar concept was exploited in other kinds of sensor (wood probe) for the building sector.[47,48] Hence, preliminary tests were performed to check the functioning of the Watermark sensor in substrates different from soil, in particular brick powder, sands having different grain sizes and solid bricks in which a hole was drilled and the sensor inserted, with and without coupling materials (different powders). The results of these preliminary tests are described elsewhere,[49] and they allowed to highlight the potential employability of the sensor also inside stiff building materials, without any coupling material, and the important role of temperature.

Therefore, the sensorized ceramic was designed and manufactured. As the moisture sensor is 22 mm in diameter and 76 mm in length, a cylindrical element was core drilled from a solid brick. The type of brick was selected after the preliminary tests described in Section 3.3. This cylindrical element has diameter 40 mm and length 100 mm, and a hole was drilled from one side, having diameter 24 mm and length 90 mm, as in Figure 2a. The moisture probe is inserted in the hole (Figure 2b), and the entire system constitutes the sensorized ceramic plug to be inserted in the masonry, as in Figure 2c. In this phase of the research, the cable can be simply hidden along the mortar joints and/or under the render. The temperature probe is constituted by a steel rod (diameter 6 mm, length 40 mm) that can be inserted in little hole drilled in the masonry close to the moisture sensors.

3.3 | Selection of the ceramic material for the sensors

To select the brick to be used for the sensorized plug in Figure 2, the four different commercial solid fired-clay bricks described in Section 3.1 (Table 1) were tested and the results are reported elsewhere.[49] In brief, four identical sensorized ceramic plugs were manufactured using BRICKS 1–4. After bringing them to a constant and uniform moisture amount (10 wt%), the SWT values were measured. The brick exhibiting the lowest SWT was selected. The reason is that, according to the technical data sheet of the moisture sensor, the optimal measurement range is between 0 and 239 cbar, while for SWT > 239 (corresponding to low moisture contents) the measurement is less reliable. The brick selected for the manufacturing of the plug was BRICK 1.

3.4 | Calibration of the sensorized ceramic plug

A calibration was necessary to derive the percentage of moisture in the brick cylinder (wt%) from the measured SWT values (cbar), and a procedure was purposely set up, as no examples of calibration for non-soil materials were found in the literature.

The achievement of a uniform and constant moisture distribution in the brick cylinders was obtained adapting an experimental procedure developed for cementitious samples.[50] The idea consists in letting the sample absorb the amount of water corresponding to a certain moisture percentage and sealing it for the time necessary to obtain a uniform moisture in all the volume. In this case, different brick cylinders (BRICK 1, Section 3.3) were let absorb a quantity of deionized water equal to 4%, 6%, 10%, 12%, 15% and 18% of their dry mass. Then, the moisture sensing probes were immediately inserted inside the cylinders, and the whole sensorized ceramic plugs were wrapped with plastic film and duct tape, to prevent any evaporation. After the attainment of the equilibrium, indicating a uniform distribution of moisture, the SWT in the sensorized ceramics was measured. Differently from the case of cementitious materials,[50] in

FIGURE 2 Sensorized ceramic plug and its way of insertion in brick: (a) the brick cylinder, (b) the moisture sensor housed inside and (c) turning and insertion of the sensorized ceramic plug (base towards the external surface) in a brick constituting the masonry

this case, the attainment of the constant conditions was directly assessed, exploiting the sensing probe inside the cylinder (variation of SWT in 24 h <1%).

To take into account the role of temperature, the wrapped sensorized ceramics were placed inside a thermostatic chamber, at constant temperatures of 10°C, 20°C and 30°C, respectively. The temperature probe was located close to the sensorized ceramics during the entire test.

3.5 | Development of a mortar suitable for the laboratory wall models

After the calibration of the sensorized ceramic plug, a validation in small walls was necessary. For the manufacturing of these walls in laboratory, the design of a suitable mortar was needed. Hence, different mortars were prepared and investigated in terms of absorption ability. For this purpose, three cement-based mortar slabs having size $28 \times 15 \times 5$ cm^3 were prepared. The mortars were manufactured using cement, quartz sand (<2 mm) and tap water, according to following formulations:

- Mortar CEM1: CEM II/A-LL 32.5 R, quartz sand, water. Cement:sand weight ratio 1:3. Water to cement ratio 1.03
- Mortar CEM2: CEM II/A-LL 32.5 R, quartz sand, water. Cement:sand weight ratio 1:3. Water to cement ratio 0.92
- Mortar CEM3: CEM II/A-LL 42.5 R, quartz sand, water. Cement:sand weight ratio 1:3. Water to cement ratio 1.03

The W/C ratios were higher compared to current formulations of cementitious mortar, to obtain a sufficiently porous media to slow down capillary rise without blocking it.

After 28 days curing (relative humidity >98%, room temperature) and subsequent oven drying (48 h at 70°C), three brick walls were built over the mortar slabs (Figure 3). The idea of using a basis having lower porosity than bricks was aimed at slowing down the rising water flow and obtaining a progressive decrease of moisture with height. The walls built on mortars CEM 1, CEM2 and CEM3 were named C1, C2 and C3, respectively. Each wall consisted of six bricks (type: BRICK 2) with a thin layer of brick powder in all the joints. The brick powder provides an easy capillary path and ensures that the walls can be quickly dismantled and modified, if necessary. Deionized water was put in the basins under the wall models, keeping a constant water head of 2 ± 1 cm. The walls absorbed water by capillarity for 30 days, then the moisture at different heights was measured through the technique developed in Sandrolini and Franzoni.[12] In brief, the method consists in drilling a hole in the brick (diameter 14, length equal to 3/4 of the brick) and inserting inside it some fragments of the same brick in which the hole was made. The hole is then closed with a plug and plasticine. Over time, the fragments were shown to reach thermo-hygrometric equilibrium with the surrounding material, meaning that the moisture in the fragments becomes identical to that of the surrounding brick. It is therefore possible to carry out a gravimetric measurement of moisture extracting the fragments from the hole and determining their moist and dry mass, the latter obtained by oven drying at 100°C until constant mass. Moisture is calculated as $\textit{Moisture}\,(\text{wt\%}) = \frac{\textit{moist mass} - \textit{dry mass}}{\textit{dry mass}} \times 100$. At the end of the measurement, the same fragments can be inserted again in the holes for the next measurement. In this way, it is possible to monitor moisture in masonry repeating the test always in the same bricks. Especially, in historical masonry, this involves two

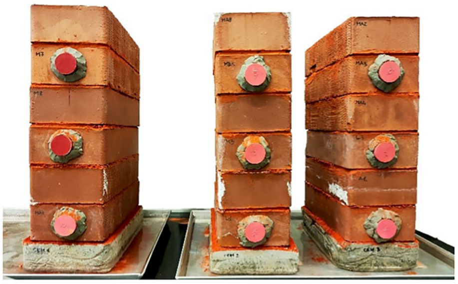


FIGURE 3 Testing walls C1, C2 and C3 (from left to right) for the measurement of moisture content by gravimetry. It is possible to observe the cement-based mortar slabs at the basis (from the left, CEM1, CEM2 and CEM3), in direct contact with water, and the three sealed holes for moisture measurement in each wall.

main advantages: (1) the destructive action is limited; (2) the variability related to measuring moisture in different bricks (heterogeneous by nature) over time is eliminated. This method of moisture monitoring was successfully used in many experimental campaigns both in laboratory and onsite.[9,19,51] This method was used to measure moisture in walls C1, C2 and C3, where holes for moisture measurement were drilled in the first, third and fifth bricks starting from the bottom and fragments taken from the same bricks used for the wall models (BRICK 2) were inserted inside the holes. Two brick fragments were inserted in each hole.

3.6 | Investigation of the moisture equilibrium between the ceramic plug and the surrounding brick

When inserted in a real wall, the sensorized ceramic plug designed in Section 3.2 will be inside a brick different from that constituting the plug itself (here, BRICK 1). This arises the need of investigating the moisture equilibrium occurring between the inserted brick cylinder and the surrounding brick where the hole is drilled. More in general, the problem is understanding what happens when a brick different from the masonry is inserted in the measurement holes; hence, the same walls C1, C2 and C3 used in Section 3.5 (and constituted by BRICK 2) were exploited. Not only fragments of BRICK 2 were inserted in the holes of the walls (Figure 3) but also fragments taken from BRICK 1 (the one used for the plug), BRICK 3 and BRICK 4. After the attainment of the equilibrium, the moisture amount of the fragments inserted in the measurement hole was measured, by gravimetry as above.

3.7 | Validation of the sensorized ceramics in wall models

Three walls were built for the validation of the sensorized ceramic plug, and they were labelled as VAL1, VAL2 and VAL3. Each wall consisted of seven bricks of the same kind of those used in Section 3.5 (BRICK 2), with 1.5-cm-thick mortar joints. The mortars were manufactured using the same formulations described in Section 3.5. In particular, CEM1, CEM2 and CEM3 mortars were used for the joints of VAL1, VAL2 and VAL3 walls, respectively. In this case, the walls were not placed on a basis made of different materials, but the first brick was in direct contact with water. Three measuring holes, respectively, in the second, fourth and sixth bricks, were created in the walls, as shown in Figure 4a,c. Each hole consists of two parts. The first part of the hole has diameter 40 mm and length 10 cm, while the second part of the hole is concentric and has diameter 25 mm and length 6 cm, reaching a total depth of about 2/3 of the brick. In the second part of the hole, having smaller diameter, three fragments of the same brick of the wall (BRICK 2) were placed, for the gravimetric measurement of moisture. In the first part of the hole, having larger diameter, the sensorized ceramic plug was inserted, keeping the open base on the internal side, as shown in Figure 4b. In this way, it was possible to carry out the measurement of moisture with the two methods exactly in the same hole, overcoming any problem of bricks' heterogeneity.

After a curing period of 4 months, the walls were put in contact with deionized water. A water head of 2 ± 1 cm was maintained inside the basins, by periodically refilling them. The moisture amount was continuously monitored using the sensorized ceramic plugs, until the values of SWT became constant (variation in 24 h <1%). This happened after about 30 days of capillary absorption. After taking the SWT measurement, the brick fragments were immediately extracted from the holes, to carry out the gravimetric measure, which was subsequently compared with the values provided by the sensors, averaged over the last 4 h of measurement. The temperature probe was left close to the model-walls for the whole duration of the test.

3.8 | Testing in real historic masonry

The last phase was the pilot application of the sensorized ceramics in a real historical masonry. The location selected for the experimental campaign was the Monumental Certosa cemetery in Bologna, Italy, built at the beginning of XIX century and including structures and artefacts of different ages, having high historical and artistic value. Many masonries show evident signs of rising damp, salt crystallization phenomena (both efflorescence and subflorescence) and freeze–thaw cycles, which cause severe damage to materials and lead to the detachment of valuable surface layers (plasters, paints and stuccoes) (Figure 5).

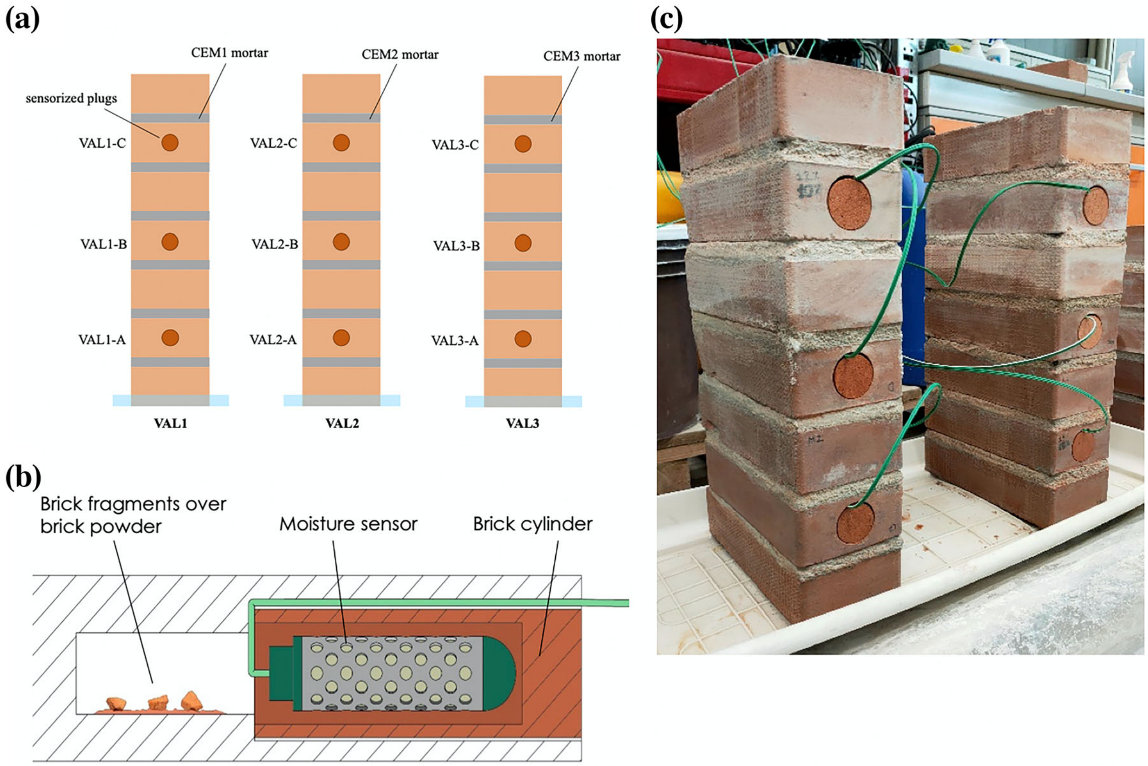


FIGURE 4 (a) Schematic representation of the testing walls used for the calibration (VAL1, VAL2 and VAL3), with the location and name of the measurement holes; (b) walls VAL2 and VAL3 during the initial wetting; and (c) scheme of a measurement hole for the simultaneous measure of moisture via gravimetry (fragments) and via sensor (external wall surface on the right)

FIGURE 5 Examples of damages due to the capillary rise of water and salts in masonries of the monumental Certosa cemetery in Bologna, Italy

Given the cultural heritage nature of the Certosa cemetery, the selection of the masonry for the pilot installation of the sensorized ceramic plugs was carried out after careful preliminary inspections. Some key aspects were considered mandatory: presence of a significant moisture amount in the masonry, feasibility of the drilling for inserting the plugs (no painted surfaces or valuable finishing), availability of a sheltered location for the control unit and presence of a socket nearby. Three walls were evaluated and finally the most suitable candidate was selected, namely, the masonry of the East side of the Cloister annexed to Cloister V. The rear of the masonry is accessible, because it overlooks an open corridor separating the annexed Cloister from Cloister V. At visual observation, this masonry seems moist up to a height of ~120 cm; moreover, the lowest part is covered by an ordinary render, probably cement-based and applied during some previous maintenance works, thus having no historic value. All these features made this wall a promising candidate for the trial testing. In April 2021, samples were collected at different heights from this wall, to measure the moisture and salts amount: N1 (10 cm from ground level), N2 (80 cm) and N3 (110 cm). Samples consist in brick powders collected by low-speed drilling (bite diameter 4 mm) at two different depths in each location: 0–1.5 and 1.5–3.5 cm.

The moisture amount was determined by gravimetry, while the nature and amount of soluble salts was determined by ion chromatography (Dionex ICS 1000), after powdering the samples (size <0.075 mm), putting them in boiling water for 10 min and filtering by blue ribbon filter.

In July 2021, three sensorized ceramic plugs were applied into the masonry, in the same locations where the moisture and salts had been measured (although not exactly in the same bricks):

- 10 cm above the ground level (sensorized plug W1), corresponding to the highest moisture amount;
- 80 cm above the ground level (sensorized plug W2), at an intermediate moisture amount; and
- 110 cm above the ground level (sensorized plug W3), where moisture is extremely low or even absent.

After locally removing the cementitious render, holes of 4 cm diameter and 10 cm depth were core drilled in the existing brick, avoiding the mortar joints. No water was used in the drilling operation. Then, the sensorized ceramic plugs were inserted in the holes (Figure 6, left). A compatible render was applied for the repointing of the masonry. The cables were fixed along the corners of the masonry and/or covered by the new render (Figure 6, right). The temperature probe was also inserted in the masonry after drilling a 4 mm hole, in the location shown in Figure 6. The cables were connected to the control unit, which was positioned in a sheltered location, for the remote transmission of data. The monitoring activity started in July 2021 and is presently running, being planned to last for at least 1 year, to collect information on seasonal variations of moisture. In this paper, the data until April 2022 are presented.

The climatic data in terms of air temperature and relative humidity and rain were collected through the Pegasus database of the local Environmental Agency ARPAE ER (Agenzia Regionale per la Prevenzione, l'Ambiente e l'Energia dell'Emilia—Romagna, Italy) throughout the same period of monitoring (19 July 2021 to 30 March 2022). The data refer to the Certosa location and are obtained by interpolation of the data collected through the climatic monitoring network.

4 | RESULTS AND DISCUSSION

4.1 | Calibration of the sensorized ceramic plug

The SWT values were measured in the sensorized ceramic plugs for different moisture amounts and at different temperatures (10°C, 20°C and 30°C), and the results are reported in Figure 7. It was possible to draw linear interpolation curves for each of the selected temperatures, which fit the SWT values very well ($R^2 = 0.9756$ at 30°C, 0.9672 at 20°C, 0.9895 at 10°C); hence, a linear correlation between SWT and moisture amount, also depending on temperature, was inferred. All the interpolation lines exhibit a very similar slope; hence, they were considered basically parallel, while the SWT values considerably increase when temperature decreases. The values >239 cbar were not included in Figure 7, as they are outside the recommended measurement range of the sensing probe (0–239 cbar).

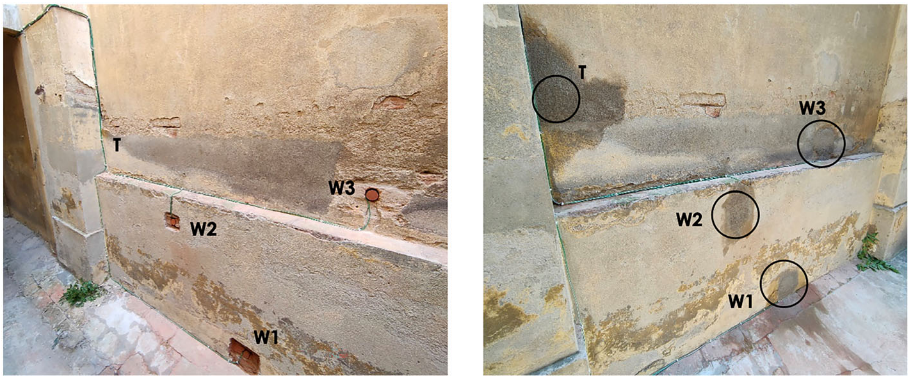
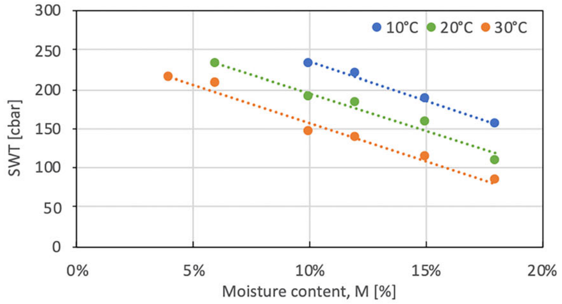


FIGURE 6 Masonry of the Certosa cemetery selected for the pilot testing: immediately after the insertion of the sensorized ceramic plugs W1, W2 and W3 (on the left) and immediately after the local repointing of the render (on the right). The location of the temperature probe (T) is highlighted as well.



T	Equation
10°C	SWT = -972.10 · M% + 332.06
20°C	SWT = -957.29 · M% + 290.30
30°C	SWT = -969.16 · M% + 255.13

FIGURE 7 Data obtained during the calibration of sensorized ceramic plugs in climatic chamber at 10°C, 20°C and 30°C (the SWT values >239 cbar were neglected, as explained in the text) and linear interpolation curves (equations in the table on the right)

These results allowed to determine the empirical equation to calculate the moisture amount from SWT and temperature:

$$SWT = A \cdot M\% + B(T), \tag{1}$$

where *SWT* is the soil water tension (cbar), *M%* is the moisture amount in the sensorized plug (wt%), *A* is a coefficient calculated as the average slope of the three calibration lines (Figure 7) and is equal to −966.18 and *B*(*T*) is a coefficient depending on the temperature *T* (°C), which was determined from the experimental data in Figure 7 and hence resulted equal to

$$B(T) = -3.8465 \cdot T + 369.43. \tag{2}$$

Therefore, the *M%* value can be calculated as

$$M\% = \frac{(SWT - 369.43 + 3.8465 \cdot T)}{-966.18}. \tag{3}$$

This equation was introduced in the online application to allow a direct remote monitoring of the moisture amount.

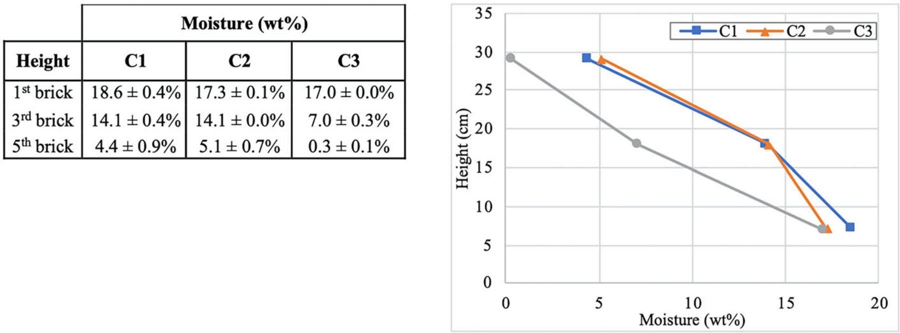
4.2 | Development of a mortar suitable for the laboratory wall models

After 30 days of water absorption in the walls C1, C2 and C3, the brick fragments were extracted from the sealed holes and their moisture amount was measured by gravimetry, according to the procedure explained above. The brick fragments were of the same kind of the bricks constituting the walls (BRICK 2). The results are reported in Figure 8.

All the walls exhibited basically saturated conditions in the lowest point and a decreasing moisture content with height, showing that the insertion of all the mortar slabs at the basis was successful in slowing down the capillary absorption flow. The behaviour of the mortars CEM1 and CEM 2 was comparable, and in fact, the moisture distribution is similar in walls C1 and C2, where the intermediate point is still quite wet and the highest one exhibits a limited moisture (~5 wt%). In wall C3, the decrease of moisture with height is sharper, and the highest measurement point is basically dry, consistently with the presence of 42.5R cement in CEM3 mortar; hence, mortar CEM3 seems the most effective in slowing down the capillary flow.

4.3 | Investigation of the moisture equilibrium between the ceramic plug and the surrounding brick

The moisture values determined in the different kinds of brick fragments inserted in the measurement holes of walls C1, C2 and C3, also including the fragments of BRICK 2 already reported in Figure 8, are reported in Table 2, both in



Height	Moisture (wt%) C1	C2	C3
1st brick	18.6 ± 0.4%	17.3 ± 0.1%	17.0 ± 0.0%
3rd brick	14.1 ± 0.4%	14.1 ± 0.0%	7.0 ± 0.3%
5th brick	4.4 ± 0.9%	5.1 ± 0.7%	0.3 ± 0.1%

FIGURE 8 Walls C1–C3: moisture amounts in the fragments inside the measurement holes (left) and their graphical representation with height (right)

TABLE 2 Results of the gravimetric moisture measurement in C1, C2 and C3 walls, in terms of moisture amount (*M*) and degree of saturation (Φ) for the four types of brick fragments inserted in the measurement holes (two replicates per type)

		C1		C2		C3	
Height	**Sample**	***M* (wt%)**	**Φ**	***M* (wt%)**	**Φ**	***M* (wt%)**	**Φ**
1st brick	BRICK 1	20.09 ± 0.36%	1.00	20.07 ± 1.55%	0.99	19.06 ± 0.14%	0.99
	BRICK 2	**18.57 ± 0.44%**	**1.00**	**17.25 ± 0.06%**	**1.00**	**17.04 ± 0.03%**	**1.00**
	BRICK 3	21.73 ± 0.30%	1.00	24.53 ± 0.32%	0.87	24.47 ± 0.12%	0.86
	BRICK 4	26.86 ± 0.20%	0.95	20.93 ± 0.56%	1.00	20.60 ± 0.02%	1.00
3rd brick	BRICK 1	16.86 ± 0.01%	0.87	16.91 ± 0.92%	0.88	7.25 ± 0.84%	0.38
	BRICK 2	**14.01 ± 0.41%**	**0.85**	**14.11 ± 0.03%**	**0.86**	**7.04 ± 0.32%**	**0.43**
	BRICK 3	18.45 ± 0.04%	0.96	21.87 ± 0.30%	0.77	8.51 ± 0.10%	0.30
	BRICK 4	21.25 ± 0.29%	0.75	17.97 ± 0.35%	0.93	6.87 ± 0.13%	0.36
5th brick	BRICK 1	6.67 ± 0.11%	0.35	4.13 ± 0.56%	0.21	0.86 ± 0.01%	0.04
	BRICK 2	**4.39 ± 0.87%**	**0.27**	**5.14 ± 0.66%**	**0.31**	**0.27 ± 0.07%**	**0.02**
	BRICK 3	5.25 ± 0.34%	0.27	4.92 ± 0.37%	0.17	0.37 ± 0.01%	0.01
	BRICK 4	5.31 ± 1.34%	0.19	4.27 ± 0.02%	0.22	0.49 ± 0.01%	0.03

Note: The fragments “Brick 2” (results in bold) come from the same type of the bricks used to manufacture the walls C1-C3.

terms of moisture amount (wt%) and saturation degree (Φ = moisture amount/water absorption at saturation, the latter taken from Table 1). In terms of moisture amount, the different brick fragments are quite different, owing to the different porosity and microstructure of the bricks. However, when plotting the results in terms of Φ values (Figure 9), these seem quite comparable and suggest that all the kinds of brick fragments reach the equilibrium with the surrounding bricks in terms of saturation degree rather than absolute moisture amount value. This is a very important result in view of the application of the sensorized ceramic plus in real masonry walls, where the features of historical bricks are unknown. The only brick differing to large extent from the other ones is BRICK 4, which is however characterized by a great internal heterogeneity and presence of inclusions, due to its handmade manufacturing technology.

4.4 | Validation of the sensorized ceramics in wall models

The moisture amounts determined by gravimetry at the attainment of the equilibrium in walls VAL1, VAL2 and VAL3 are reported in Figure 10, together with the moisture values given by the sensorized probes inserted in the same measurement holes. The latter values are shown for the entire period of monitoring, that is, since the introduction of water in the basins under the walls. In terms of gravimetric moisture amount, VAL1 is basically saturated in the first two measurement points, while the highest point exhibits a limited moisture. VAL2 is saturated in the first two points and

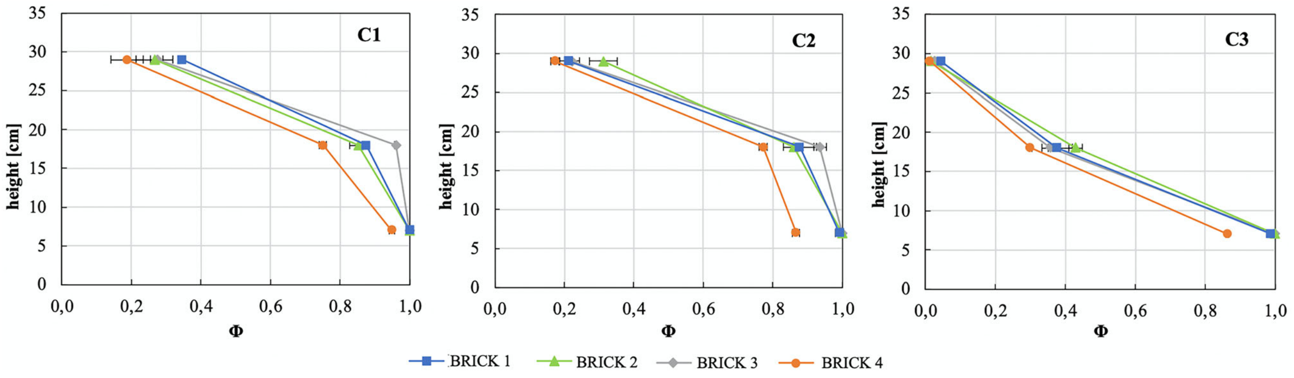
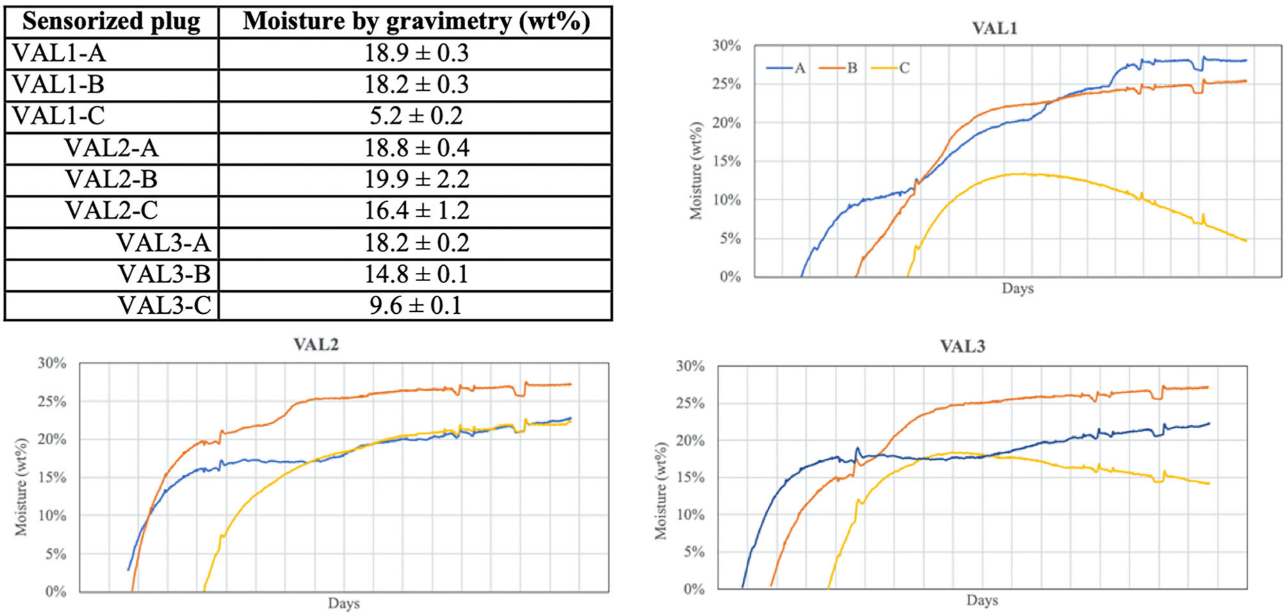


FIGURE 9 Degree of saturation variation with height for the four types of brick, respectively, in C1, C2 and C3 walls. The height of the measurement point was measured from the basis of the cementitious mortar slab.



Sensorized plug	Moisture by gravimetry (wt%)
VAL1-A	18.9 ± 0.3
VAL1-B	18.2 ± 0.3
VAL1-C	5.2 ± 0.2
VAL2-A	18.8 ± 0.4
VAL2-B	19.9 ± 2.2
VAL2-C	16.4 ± 1.2
VAL3-A	18.2 ± 0.2
VAL3-B	14.8 ± 0.1
VAL3-C	9.6 ± 0.1

FIGURE 10 Walls VAL1, VAL2 and VAL3: moisture determined by gravimetry at the end of the test (in the table) and moisture measure in continuous by the sensorized plugs in the three measurement holes of each wall

also the highest one is close to saturation. VAL3 is exhibits a clear decreasing amount of moisture with height. These results only partially reflect what expected based on the preliminary tests on mortars (Section 4.2). Although the use of CEM1 and CEM2 mortars in VAL1 and VAL2 produced similar outcome, as in the preliminary tests, the slowing down of the capillary flow was less than expected. Mortar CEM3 was the most effective in causing a decreasing moisture distribution with height, as in the preliminary tests, but less than expected. These findings are thought to be due to the fact that the mortar slabs (Section 4.2) and the mortar joints of the walls had different curing speeds, the speed being lower for the joints, due to a lower availability of CO_2. The curing of the mortar joints (likely far from being complete) surely played a key role, as the capillary water flow could leach some calcium hydroxide still present in the mortar,[51] increasing its porosity and hence its sorptivity. The different thickness of the mortar joints with respect to the slab may have played a role, too. Further tests are presently running to elucidate this aspect.

As far as the sensorized plugs are involved (Figure 10), the sensors measured moisture starting from the lowest one, that is, as soon as they were reached by water, which happened in 7–10 days even for the highest point. During the initial progressive wetting of the walls, in which unsaturated water flow was present and absorption was quick, moisture did not constantly increase but some transient decrease was present, especially in points A and B, likely due to some temporary consumption of the water in the basins (weekends, evaporation higher than expected or simply unexpected

TABLE 3 Moisture and salts in the brick samples collected from the masonry in the Certosa cemetery by low-speed drill in April 2021

Sample	Moisture (wt%)	Cl^- (wt%)	NO_3^- (wt%)	$SO_4^=$ (wt%)
N1 (depth 1–1.5 cm)	11.1	0.08	0.04	0.07
N1 (depth 1.5–3.5 cm)	15.3	0.04	0.02	0.04
N2 (depth 1–1.5 cm)	6.0	0.10	0.07	0.48
N2 (depth 1.5–3.5 cm)	9.6	0.13	0.08	0.45
N3 (depth 1–1.5 cm)	2.0	0.11	1.33	1.07
N3 (depth 1.5–3.5 cm)	1.4	0.12	1.02	0.69

changes in laboratory temperature). At the end of the test, comparing the moisture values obtained by gravimetry and those provided by the sensorized plugs (Figure 10), some interesting remarks can be done. The moisture distribution with height found with gravimetry was found also by the sensors, but with some difference in the values. In VAL1, the points A and B seem similar and basically saturated, while point C exhibits a low moisture (about 5%), as in the gravimetric measurement. In VAL2, all the points exhibit basically saturated conditions and the highest moisture amount is in point B, as in gravimetry. In VAL3, points A and B are basically saturated, but there is a switch between them in the moisture values compared to gravimetry, while point C is correctly the less wet. However, it is clear that the values provided by the sensors almost systematically overestimate the moisture amount with respect to gravimetry, being the saturation at ~22–28 wt% rather than at ~19 wt%. This effect is thought to be due to two main reasons:

- The temperature used for the calculation of the moisture according to Equation 3 was not measured inside the holes, but in air, close to the walls. Some mismatch between the temperature in the holes and the one measured by the sensor might lead to errors in moisture calculation.
- In bricks, with very high moisture and considering that capillary rise involves a continuous water flow, it is possible that some water droplets condensate inside the sensorized probe. This might cause an overestimation of the moisture amount.

4.5 | Testing in real historic masonry

The brick samples collected by drilling from the historic masonry wall in the Certosa cemetery in April 2021 were analysed, and the results are reported in Table 3, allowing to make the following observations:

- The moisture amount in the superficial layer (0–1.5 cm) is lower than that inside the wall (1.5–3.5 cm) in samples N1 and N2, located 10 and 80 cm above the ground level, respectively. This is consistent with the effect of surface evaporation, well-documented in the literature on rising damp in walls.[52] In sample N3, the two values of moisture at the surface and inside the brick are similar; however, they are both very low, indicating that the masonry is basically dry there.
- Focusing on the samples collected deeper in the wall (depth 1.5–3.5 cm), the lowest brick exhibits a very high moisture amount (N1, 15.5%), the second a remarkable but much lower amount (N2, 9.6%), while the highest one is basically dry (1.4%, N3), as expected for a wall affected by rising damp.
- In terms of soluble salts, again the results are in line with what expected for a typical masonry affected by rising damp. In fact, the precipitation and accumulation of salts is concentrated close to the equilibrium line (sample N2, Table 3), where evaporation is more intense.[52] Sulphates and nitrates are the major salts, likely deriving from the soil and the burials, respectively.

After this preliminary survey, the wall was considered suitable for the pilot testing.

On 19 July 2021, the sensorized ceramic plugs and the T probe were installed in the selected locations in the masonry and the monitoring started. The collected data are shown in Figure 11 for the first month and in Figure 12 for the entire monitoring period July 2021–April 2022. For comparison's sake, the climatic data during the same period, collected close to the cemetery, are reported in Figures 13 and 14. All the data collected allow to make the following observations:

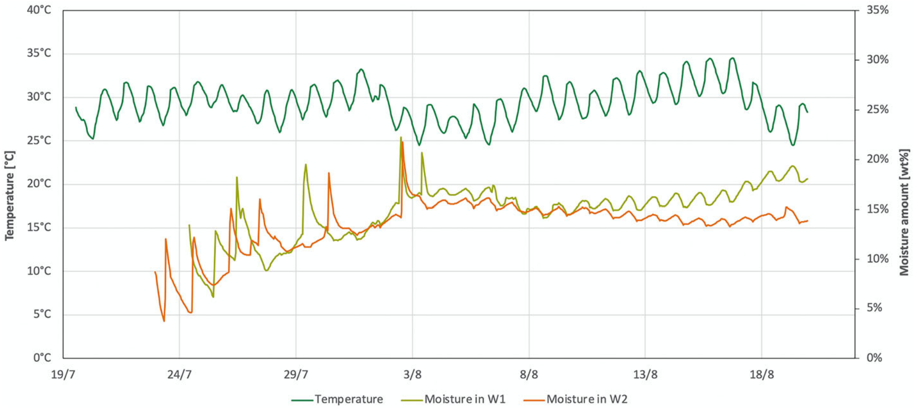


FIGURE 11 Temperature and moisture amounts measured by the sensorized plugs in the masonry at the Certosa cemetery during the first month of monitoring

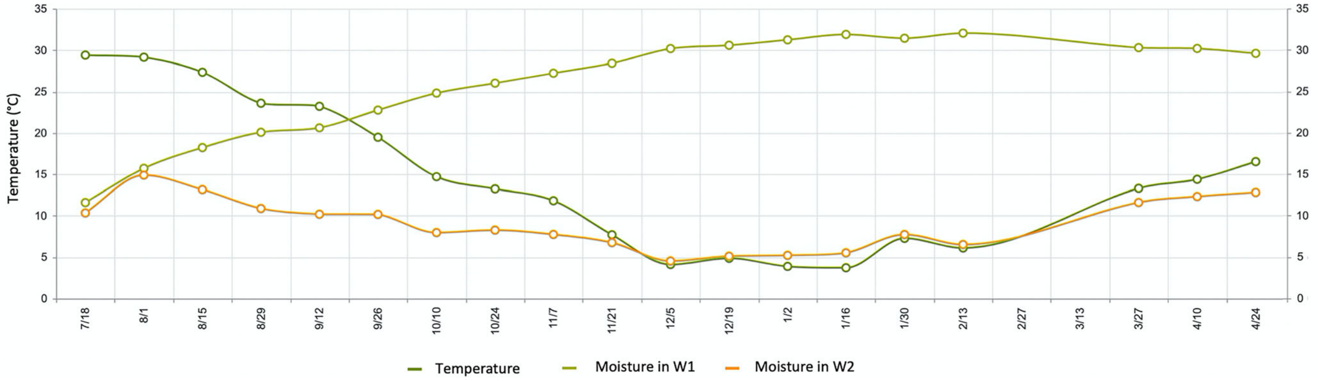


FIGURE 12 Temperature and moisture amounts measured by the sensorized plugs in the masonry at the Certosa cemetery during the entire monitoring period

- The T probe in the masonry was clearly influenced by the daily thermal excursion (Figure 11), although in an attenuated way compared to external air in the area (Figure 13), as expected. The probe recorded the expected seasonal variation from summer (~30°C in August) to autumn (−5°C or less in December), to spring (~15°C in April).
- After the first 15 days in which the moisture in W1 and W2 sensors was very instable due to their progressive wetting, the values became more stable and 1 month after the installation of the sensors, moisture was about 17 wt% in the lowest point (W1) and 13 wt% in the intermediate point (W2); hence, the values measured by the sensors can be considered quite consistent with the moisture distribution found in April 2021 by gravimetry. It is noteworthy that the measurement in April was carried out not in the same bricks where the sensors were installed, although very close. The highest sensor (W3) did not provide any value, indicating that the relevant zone is basically dry, as in April.
- In the lowest sensor (W1), moisture progressively increased and became approximately constant in October, reaching a value around 23% to 25%, while in the intermediate point (W2), it progressively decreased, reaching a value around 8% to 9% in October. These data are quite difficult to interpret. In 2021, which was a very dry year,[53] the level of the water table in the plain were Bologna is located varied between −2.5 m in Spring to −3.5 m in Autumn,[54] suggesting that moisture in the wall should decrease passing from Spring to Autumn. On the other hand, the relative humidity of the air, which is a parameter boosting or hindering the evaporative capacity of the wall, increased in the same period (Figure 13), although always with big fluctuations. Finally, no particular relationship seems to exist between rain events (Figure 14) and moisture in the wall. Crossing all these data, it seems that moisture in W2 was strongly affected by the decrease of the water table, not particularly affected by the increase of relative humidity (likely due to

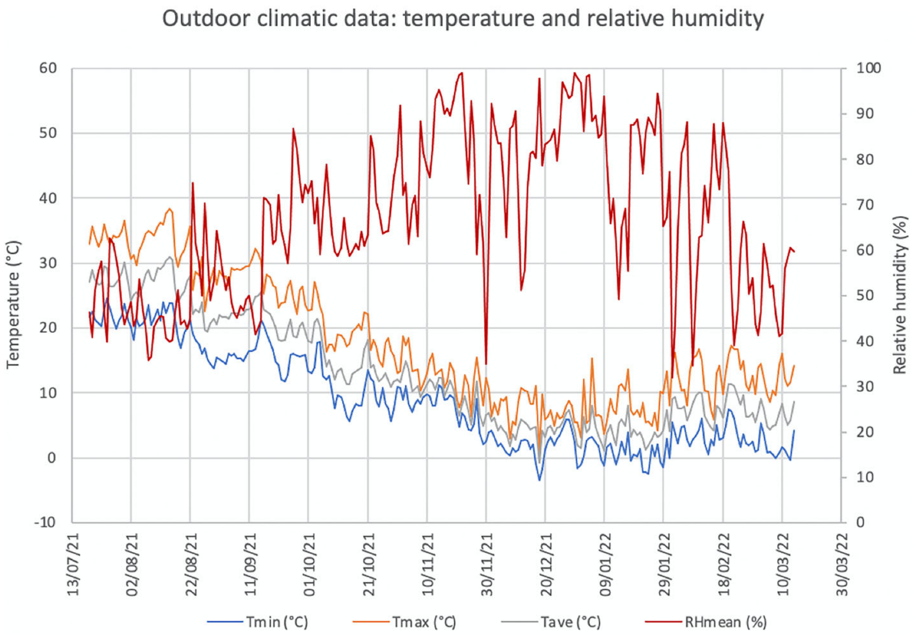


FIGURE 13 Daily climatic data collected by the ARPAE monitoring network,[53] during the period of monitoring: minimum, maximum and average air temperature and average relative humidity

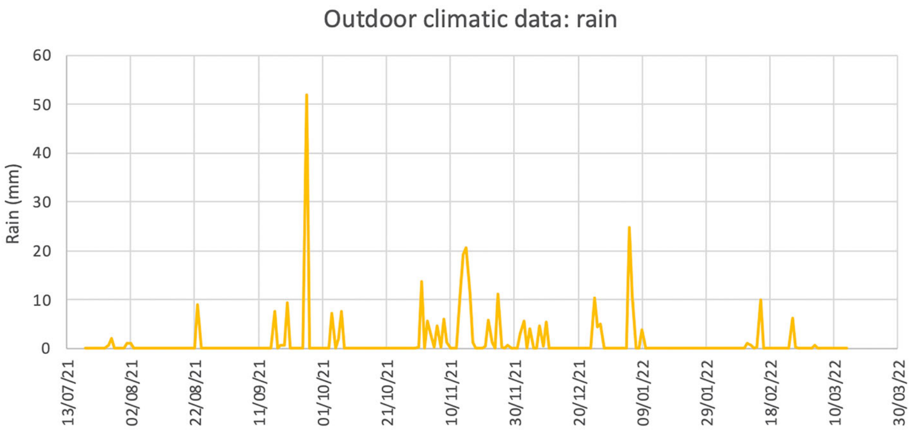


FIGURE 14 Rain in Bologna during the period of monitoring[53]

the cement-based render present over the wall surface, limiting the evaporation rate) and not affected at all by the rainfall events. Thus, the reason for the continuous moisture increase in the lowest sensor W1 should be ascribed to different reasons that the absorption-evaporation flow in the masonry and rather to the sensing plug, also considering that the moisture amount measured in winter (30% to 32%) was well about the typical moisture amount at saturation for historic bricks (usually 20% to 25%). This discrepancy can have different explanations: (1) The T values used in Equation 3 were not measured at each sensor, but in a single sensing probe in the same wall (Figure 5), where temperature could be different; (2) during December and January, the temperature in the T probe was around 4°C to 5°C and probably even lower in sensor W1, thus in a range of temperatures were calibration was not carried out; and (3) the prolonged capillary flow (jointly with the low temperature) may have caused the condensation of some droplets of water over the sensor's surface, thus leading to an overestimation of moisture, as suggested by the data from validation. Considering that the soluble salts in W1 are very limited (Table 3) and that the sensor is stated to be not affected by the salinity of the soil, salts seem not involved in the high moisture measured by the sensor. These aspects are currently under investigation.

5 | FUTURE STEPS AND EXPECTED SCENARIO

The results obtained so far are extremely encouraging towards the development of reliable and robust sensorized plugs for onsite monitoring of moisture in historic masonry walls, although some aspects need to be fully elucidated and improved. From the point of view of the interactions between the ceramic envelope and the masonry substrate (historic bricks), it will be necessary to cope with two main issues: (i) A systematic evaluation of the impact of soluble salts on the measurement is necessary, through laboratory tests in which the main salts currently present in historic structures should be considered; (ii) more experimental data from laboratory and onsite tests are necessary to confirm and better assess the capability of the sensorized plug to measure the moisture in the masonry in terms of saturation coefficient. From the point of view of the sensor, it seems necessary to solve three main issues, to allow its application to historic buildings: (i) the miniaturization of the sensor, to limit the destructive action for its installation; (ii) the elimination of the cables; and (iii) the coupling of the temperature and moisture probes in the same plug, to skip the problems related to measuring temperature in a different location with respect to moisture.

Any type of masonry wall is potentially interested in the application of the developed sensorized ceramic plugs. The plug can be installed both in a header and in a stretcher brick, so in any masonry wall. Inserting the plug in the bricks allows to overcome the possible problems related to measuring moisture in the mortar joints, which could be variable, deteriorated, or even repointed. The sensorized probe provides an in-depth measurement of moisture, which is considered enough to avoid the influence of microclimatic conditions. For masonry exhibiting an extremely high thickness, the probe could slightly underestimate the moisture present in the 'core' of the wall, but actually, it is the moisture in the first layer from the surface which determines the deterioration processes affecting the materials and the other problems described above.

As a future scenario, the sensorized ceramic plugs should be inserted at different heights in the masonry (as in Figure 6), which allows the monitoring of moisture variations quite consistently, as demonstrated also in other studies where different measurement techniques were used.[19] A selection of the most significant locations for the insertion of the plugs should be done preliminarily for each building, as in this study, by different destructive and/or non-destructive methods. In this way, a significant set of data can be collected also by a limited number of monitoring points. In fact, only a limited number of sensors can be usually inserted in historic and heritage structures, unless a drastic miniaturization of the sensors is achieved. An alternative and non-destructive approach could be the mapping of moisture distribution by the application of a high number of sensors on the surface of the masonry, but in this case, transient variations of moisture are expected due to the influence of the external atmosphere (temperature, sun radiation, air relative humidity, rain, wind, etc.), making the data collected more erratic and difficult to interpret.

The remote monitoring of moisture could be coupled also with an alert system that gives a warning when the structure reaches a too high level of moisture and indicates that repair measures are needed. The development of such alert system goes beyond the scope of the present paper. Moreover, the amount of moisture that can be tolerated in a masonry building depends on its features, such as the presence of decorations and valuable finishings and the aggressiveness of the environment; hence, it could be fixed for each specific building.

In the future, the developed plugs could be applied also to stone masonry, where the importance of monitoring moisture was already recognized and some sensorized solutions were proposed.[48]

6 | CONCLUSIONS

In this paper, a sensorized plug was designed, constituted by a moisture sensing probe inserted in a brick envelope. The idea of embedding the sensor inside the ceramic envelope derives from the awareness of the extreme heterogeneity of historic bricks even within the same masonry, which makes any calibration of the sensor impossible. By embedding the sensor inside a material of known characteristics, a calibration is possible, while the equilibrium attained between the envelope and the surrounding brick will be in terms of saturation degree rather than absolute moisture content.

The results obtained in the present study allow to derive the following conclusions.

- The sensorized plug was successfully calibrated for the ceramic material (brick) selected for the envelope, highlighting the dependence on temperature and allowing to obtain an equation that correlates the moisture amount (wt%) with the SWT and the temperature measured by the sensors.

- The ceramic envelope used for the sensor is expected to equilibrate with the surrounding bricks in terms of saturation degree, providing valuable information about the level of wetting of the wall, independently from the actual porosity of each single historic brick.
- The validation of the ceramic plugs was carried out in laboratory walls that were built using purposely designed cement-based mortars. The phenomenon of rising damp that occurs in real masonry was successfully reproduced in the laboratory walls, which in fact exhibited a decreasing moisture amount with height. However, the incomplete curing of the mortar joints is thought to be responsible of a higher sorptivity than expected, due to the leaching of lime caused the ascending flow.
- The validation showed that the sensorized plugs are successful in detecting the moisture distribution in the laboratory walls, but some overestimation of the moisture amount was found, probably due to some condensation inside the plugs. Temperature measured not directly inside the plugs but in the laboratory may have affected the results as well.
- Three sensorized plugs were installed in a real historic masonry affected by rising damp and they successfully allowed to monitor moisture and temperature over a period of about 10 months. The plugs provided results consistent with those previously found by sampling and gravimetry. At the basis of the wall, where moisture approaches saturation, the sensor overestimated the moisture amount, as in the validation phase. At a height of 80 cm, the sensor showed that moisture strongly depends on the level of the underground water table, while is basically unaffected by rain and air relative humidity, the latter having probably a weak influence due to the presence of a compact render on the surface. The fact that temperature is measured inside the wall but in a different position with respect to the sensors may constitute a drawback, as seen in the validation phase. The highest point was confirmed to be basically dry.

The new sensorized ceramic plug developed in this paper is considered extremely promising for application to historic masonry buildings, although some further research is necessary to clarify some aspects and to improve the plug, in view of a concrete and extender application in the field. Moreover, the methodology and research approach proposed in this paper may be potentially applied also to different kinds of sensing probes, which could be coupled with a ceramic envelope and used as plugs to be inserted in the masonry.

A significant contribution to the development of new sensorized solutions for masonry could come also from numerical simulation, which allows to consider several different scenarios without multiplying the experimental effort. This is true especially in the validation phase, where laboratory walls having fully known characteristics are employed.

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AUTHOR CONTRIBUTIONS

Elisa Franzoni: Conceptualization; methodology (lead); formal analysis (equal); funding acquisition; project administration; supervision; validation (equal); visualization (supporting); writing – original draft (equal); review and editing (equal). **Mattia Bassi:** methodology (supporting); data curation; formal analysis (equal); validation (equal); visualization (lead); writing – original draft (equal); review and editing (equal).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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