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New sensors for moisture monitoring in historic walls: preliminary results

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Abstract. The presence of moisture in historic masonry walls represents one of the main sources of decay for cultural heritage and materials, besides causing unhealthy indoor conditions and worsening the thermal performance of the building envelope. In fact, moisture causes and/or exacerbates different deterioration mechanisms, such as salt crystallization, freeze-thaw cycles, biological growth, etc. Given the importance of moisture in materials, there are many techniques aimed at determining moisture content in structures, but the most common ones only provide qualitative results or do not allow reliable repeated measurements over time, which is a severe limitation when continuous monitoring is necessary.

In this perspective, the MIMESIS project (funded by Emilia-Romagna Region, Italy) aims at developing a range of sensorized materials for the remote monitoring of moisture, temperature, pH and detachment, useful to determine the ‘health state’ of historic buildings. It is also expected that the sensorized materials give a warning when critical situations are reached, allowing to carry out adequate interventions before irreversible damage occurs.

In this paper, a brick-based sensor suitable for measuring moisture content in masonry was developed and tested. The sensing element was originally designed for agriculture, to measure the ‘soil water tension’, hence an investigation about the applicability to building materials and a calibration in bricks was necessary. The results are encouraging and suggest that this new sensorized brick could be applied for the continuous monitoring of moisture in historic masonry.

Keywords: Rising damp, historic masonry walls, Moisture measurement, Monitoring, Calibration.

1 Introduction

One of the main problems of historic buildings is the presence of moisture in porous materials, such as brick, natural stone, mortar, plaster, etc. Moisture leads to deterioration of materials, unhealthy indoor conditions, and a decrease of the walls’ thermal insulation. In particular, the presence of water in materials leads to damage from salt crystallization, freeze-thaw cycles, chemical and biological attack, wind erosion, etc., thus threatening historic buildings’ conservation [1–5]. Hence, a fundamental step in any restoration project is to determine the moisture content of the elements affected by damp, in order to evaluate if it is necessary to take measures to reduce it. Notably, if adequate measures are not taken, interventions made on moist materials will be useless, if nor counterproductive [3]. Unfortunately, phenomena such as capillary rise from ground, rain precipitation, surface condensation or broken pipes and gutters may act together as sources of water and their complete elimination is very difficult [4]. Besides determining moisture content and distribution inside the walls, its monitoring over time is equally important, to prevent damage to cultural heritage [3]. However, measuring moisture in historic buildings is not an easy task, for many reasons. First of all, the authorities in charge of cultural heritage allow very limited destructive operations in buildings, thus excluding too invasive techniques. Secondly, many non-destructive techniques provide data that require a calibration in order to obtain the moisture content, and this is a severe problem in historic buildings, due to the limited destructive actions allowed and the heterogeneity of materials [1, 3, 6]. In the case of monitoring over a period of time, such measurement is even more challenging [4].

The most accurate and reliable method to determine moisture content in walls is commonly considered gravimetry, which consists in collecting samples and determining their moisture amount by comparing the wet mass and the dry one, the latter obtained after oven drying. This method is very simple, but exhibits several disadvantages, because it provides only local information, is time consuming, destructive and non-repeatable, and does not allow monitoring over time [7]. Moreover, the collection of the samples is a delicate operation especially in heritage buildings, as it is necessary to minimize the number and size of samples, without losing representativeness. For this reason, gravimetry is often used to calibrate non-destructive methods or during preliminary survey campaigns [1, 3, 7, 8], rather than for monitoring.

In recent years, research in this field has focused on the development of non-invasive probes and remote techniques that do not cause any damage to buildings having historic and artistic value [1, 4, 7, 9–14]. These are generally indirect techniques, in which a parameter depending on the moisture content of the material is measured [1]. The most diffused methods are based on electrical properties, such as resistance, impedance, capacitance and dielectric constant, which are strongly influenced by the presence of moisture [5]. Both invasive and non-invasive sensors have been developed [1, 4, 10]. However, the results are affected by the characteristics of the material, state of the surface, sensor/surface contact, frequency of current used and, mainly, temperature and salt content. The calibration is complex, due to the heterogeneity of historical building materials and it could be necessary to know their absorption properties and salt content to have a more accurate measurement [4, 5, 15]. An interesting example of method based on electrical resistance is the so-called ‘gypsum blocks’, designed for continuous monitoring of soil moisture in agriculture [16]. It exploits a low-cost sensor made of a cylindrical block of gypsum mounted on a plastic base and provided with two electrodes. The moisture in the block goes into equilibrium with the surrounding material and the electrodes allow to measure the electrical resistance. The main advantage of this technique is that gypsum, rich in calcium and sulphate ions, is not sensitive to the presence of salts, acting as a buffer towards the effect of salts on electrical conductivity [16, 17]. Other quite diffused techniques are based on the use of microwaves, where an electromagnetic field interacts with the material and water contained in it, losing part of its energy, according to an extinction coefficient which depends on the dielectric properties of the dry material and the moisture amount [1, 6, 15, 18, 19]. Thanks to the high frequency of microwaves, the presence of salts is not an issue [2, 5, 6, 19].

Another completely non-invasive method to detect moist zones in a walls is infrared thermography, as the water evaporation from the masonry surface causes a lowering of the temperature and can be easily seen [1, 4, 5, 15]. Infrared thermography is normally used to obtain qualitative information, while quantitative techniques should be used to quantify moisture. Moreover, the measurement refers only to a surface layer of the material, influenced by atmospheric conditions [1, 15]. Other methods exploits the thermal conductivity of materials, which is not affected by salt presence [1]. The sensors are thermocouples, which can heat the materials and register temperature increase, allowing to determine the moisture content, provided that the heat capacity of the dry material is known [1]. A more recently introduced thermal method exploits optical fibres, which are chemically inert, light, remotely controllable and allow a mapping [1]. They are widely used in distributed temperature sensing (DTS) in agriculture for the detection of soil moisture over long distances [14, 20].

As shown above, many methods and sensors are available to measure moisture in porous building materials. However, most of them only provide qualitative information and a calibration on each material would be necessary, which is basically impossible in historical buildings that are made, by their nature, of heterogeneous materials and often even from different periods. 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, Italy, aims at developing a sensorized ceramic material to be applied in masonry walls, which is able to overcome the difficulties described above and to provide reliable values of moisture (liquid water content). The new sensor is expected to provide data remotely and in real time, giving a warning in case of 'critical' moisture conditions and preventing irreversible damages.

2 Materials and methods

2.1 Sensorized ceramic material

A preliminary research was carried out on the sensors available in the market for moisture measurement. Particular attention was paid to the possibility to integrate the sensors into a ceramic material (brick) and to the ability to provide remote and real time data. Finally, a type of sensor was selected, which is currently used in agriculture ('Watermark Soil Moisture Sensor', by IRROMETER Company, Fig. 1a). It is an electrical resistance sensing device used to measure the 'soil water tension' (SWT, in cbar), which represents the tension required by the roots of the plants to extract water from soil, hence providing an indication about the need of irrigation [21, 22]. The sensor consists of a pair of corrosion-resistant electrodes encapsulated in a granular matrix (gypsum). The diameter of the sensor is 22 mm and its length is 76 mm. It is equipped with a cable for the connection to a data collection and transmission control unit ('Plug & Sense! Smart Agriculture Pro Wi-fi' control unit, by Libelium), which allows to simultaneously connect up to three Watermark sensors and a temperature sensor (Fig. 1b). The temperature sensor is a PT-1000 probe, again used in agriculture for soil. The granular matrix constituting the Watermark sensor reaches the hygrometric equilibrium with the surrounding material in which it is fixed (generally soil) and the electrodes measure the electrical resistance of the granular matrix, finally sending the data to the collection unit. This translates electrical resistance values into SWT values through a proprietary calibration equation provided by the manufacturer. The data are sent to a cloud in which they can be seen real time, thanks to an online platform designed for the

MIMESIS project. The SWT values are plotted over time for the three moisture sensors and the temperature sensor (Fig. 2). Data are available both as single values, obtained every minute, and as hourly average.

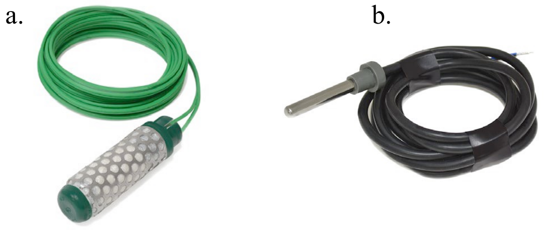
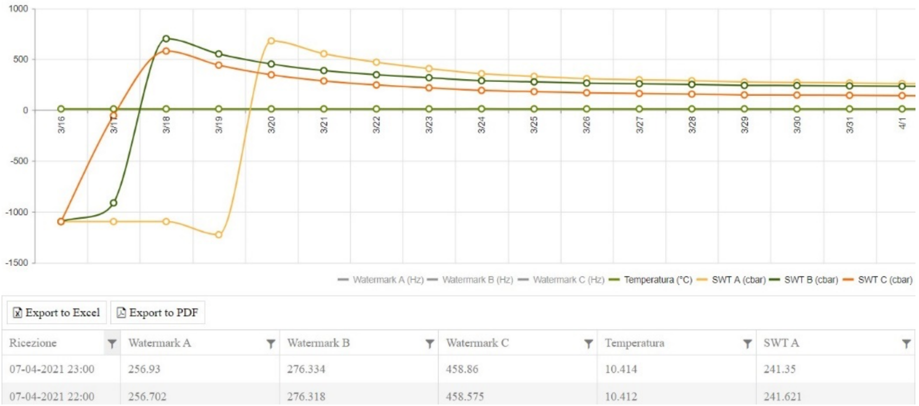


Fig. 1a: sensor selected to measure moisture content. **1b**: probe selected to measure temperature.



Ricezione	Watermark A	Watermark B	Watermark C	Temperatura	SWT A
07-04-2021 23:00	256.93	276.334	458.86	10.414	241.35
07-04-2021 22:00	256.702	276.318	458.575	10.412	241.621

Fig. 2: example of an online platform screen, where curves of SWT values over time referred to the three Watermark sensors are visible (yellow, orange and dark green curves) together with temperature curve provided by the PT-1000 probe (light green curve).

Once the moisture sensor was selected, a system to integrate it inside a ceramic material was designed. The idea was to create a sort of 'plug' to be inserted in the masonry, consisting in a cylinder of brick with the sensor embedded inside, as shown in Fig. 3. The cylinder is 40 mm in diameter and 100 mm in length, with a central hole having diameter 24 mm and depth 90 mm, suitable to insert the sensor without forcing it and without leaving too much free space between sensor and hole. The cable connecting the sensor to the control unit can be hidden in the mortar joints or under the render.

Four different types of commercial solid bricks (manufactured in Italy by IBL, SanMarco, Pica, and RDB, and here labelled as 'brick 1-4', respectively) were used for the tests, to find the most suitable one for the embedding of the sensor. According to preliminary tests, all the tested bricks have similar microstructure characteristics to those currently found (on average) in historic buildings. In this way, the sensorized ceramic plug can be considered quite similar and compatible with historic masonries, although it is well known that ancient bricks exhibit an impressive heterogeneity [4].

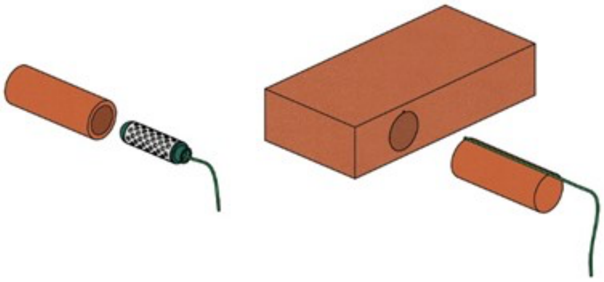


Fig. 3: scheme of the sensorized ceramic material and its way of application onsite. The brick cylinder is drilled, and the moisture sensor is positioned inside. For the application to a real masonry, the sensorized element is turned with the base towards the outside, so the sensor is more protected from the external masonry surface, and it is also more easily hidden.

2.2 Preliminary tests on the sensors

Despite a careful research in the scientific literature, no examples were found on the use of the selected sensor in applications different from agriculture. Hence, preliminary tests were carried out to understand if the sensor can be used in different substrates.

At first, the bare sensors were positioned inside loose materials (Fig. 4a), namely brick powder (obtained by grinding a sample of brick 1) and different types of sand (fine, coarse, and mixed). Then, water was added and the values of SWT were measured. Another set-up was prepared to follow a complete wetting and drying cycle, somehow simulating capillary rise from the ground. In this second set-up, the sensors were inserted in open containers (Fig. 4b) filled with the same loose materials previously used and positioned on a pack of filter paper, which was kept wet by adding tap water in the container. After wetting, the set-up was let dry at laboratory conditions and the wetting and drying curves of the sensors were monitored through the online platform, also observing the different response in the selected loose materials.

Therefore, the bare sensors were positioned inside solid bricks having size 12 × 25 × 5.5 cm^3, by previously drilling holes having diameter equal to 24 mm and depth equal to 2/3 of length of the brick. The diameter of the hole was selected in order to be only slightly higher than that of the sensor (22 mm), for the reasons above. Different coupling materials were investigated to fill the space between the sensor and the hole. One brick was left without coupling material, with the sensor simply inserted into the hole, while the others were filled with brick powder and fine sand. The hole was then sealed with plasticine and the bricks were positioned in a basin under a water head of 5 mm, to let them absorb water by capillarity up to complete saturation (Fig. 4c). After 3 days in this condition, the bricks were let dry at laboratory conditions.

2.3 Calibration of the sensorized ceramic

As the sensors are calibrated by the manufacturer for the measurement of moisture in different kinds of soils, a tailored calibration in bricks was necessary, in order to obtain the moisture content value starting from the SWT. Different tests were carried out.

In the first calibration, brick 1 was used. The methodology adopted was inspired by the experimental procedure in [23], aimed at obtaining uniformly distributed partial saturation conditions in concrete samples. In this study, cylindrical brick samples (Fig. 3) were let absorb fixed amounts of water by capillarity, corresponding to a moisture percentage [(moist mass - dry mass)/dry mass] equal to 4%, 6%, 10%, 12%, 15% and 18%. The value 18% corresponds to saturation at atmospheric pressure for the selected brick. The sensor was then immediately inserted in the cylinder and the hole sealed with plasticine, finally wrapping all the set-up with plastic film and adhesive tape, to prevent any water loss by evaporation (Fig. 5). No coupling material was used between the sensor and the brick cylinder, following the results obtained in the preliminary tests (see 3.1). Once sealed, the sensorized ceramic elements were left at laboratory until moisture uniformly distributed and became constant, which was checked by monitoring the SWT (variation in 24 hrs < 1%). The temperature probe was kept close to the samples.

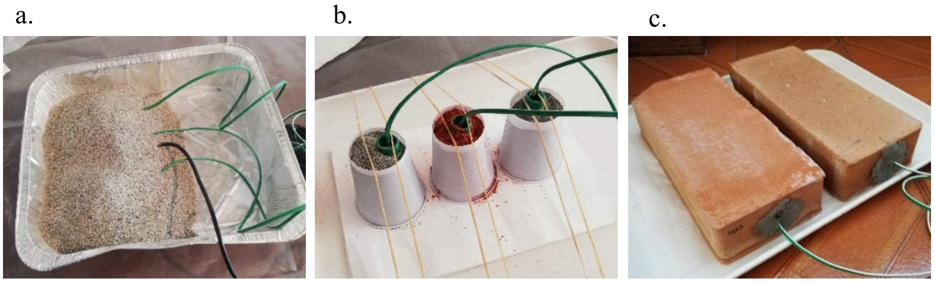


Fig. 4a: experimental set-up with the sensors inserted in sand (mixed grain size), wetted with water. **4b**: capillary rise set-up with various materials (sand with different granulometry and brick powder). **4c**: set-up with the sensors inserted in full bricks, with and without coupling material inside the hole.

Fig. 5: sensorized ceramic elements wrapped with plastic film and insulating adhesive tape during the calibration phase.

In the light of the results obtained in this first calibration test and the problems found in measuring low moisture amounts (see 3.2), new tests were carried out, following the same testing procedure described above (Fig. 5), but using: 1) different kinds of bricks for the cylinders (bricks 1-4); 2) a fixed moisture amount, namely 10%.

After this further group of measurements, a specific brick was selected as the most suitable for the manufacturing of the sensorized ceramic (brick 4) and the calibration was repeated using this material, at different moisture contents (4%, 6%, 10%, 12%, 15% and 18%), putting the wrapped cylinders with sensors inside a climatic chamber at a constant temperature of 20°C ± 1 °C.

3 Results and discussion

3.1 Preliminary tests on the sensors

From the preliminary tests carried out using loose materials and full bricks with different coupling powders, some basic observations were derived about the functioning of the sensor in substrates different from soil. In all the materials under investigation, SWT decreases as the moisture content in the material increases, as expected, and the sensor is strongly sensitive to changes in moisture content, hence the measurement in building materials seems feasible. The tests performed inserting the sensor in solid bricks with holes showed that the presence of a coupling material between sensor and hole (fine sand or brick powder) is not necessary, as the SWT values obtained with and without coupling materials were fully comparable. Moreover, comparing the SWT values obtained inserting the sensors in the perforated solid brick and in the brick cylinders, no substantial differences were found, confirming that SWT does not depend on the size of the sample in which it is inserted.

3.2 Calibration of the sensorized ceramic

The results obtained from the first calibration with brick 1 are reported in Fig. 6, where a clear correlation between SWT and moisture can be observed. However, two main issues were found. Firstly, the range of measurement of SWT recommended by the manufacturer’s datasheet is 0-239 cbar, therefore the measurement is likely less reliable for moisture <8%, which is a significant limit in the envisaged application, as a masonry exhibiting moisture in this range cannot be considered dry. Secondly, a certain degree of dispersion was found in the values, and this was ascribed to the slight temperature variations in laboratory at the different dates in which the calibration tests were carried out. In fact, monitoring SWT in the online platform showed it depends on temperature.

To overcome the first issue, further tests were carried our using different kinds of brick at the same moisture amount (10%). The results are shown in Fig. 7, where the SWT values are reported versus time, and the attainment of the equilibrium in the sensorized materials can be observed. Considering that the measurement reliability limit of SWT is 239 cbar, the most suitable brick resulted brick 4, i.e., the one which provided the lowest SWT value for the same moisture content.

Hence, brick 4 was selected to be used for the plug and a second calibration was carried out, this time at a constant temperature of 20°C, in order to overcome also the second issue found in Fig. 6 (data dispersion). The results are reported in Fig. 8, where it can be observed that only for moisture approximately below 5% the value of SWT falls above the range recommended by the manufacturer (>239 cbar), which is quite acceptable for masonry walls. Moreover, the linear equation describing the relationship between SWT and moisture fits in an excellent way with the data obtained (R^2=0.9672).

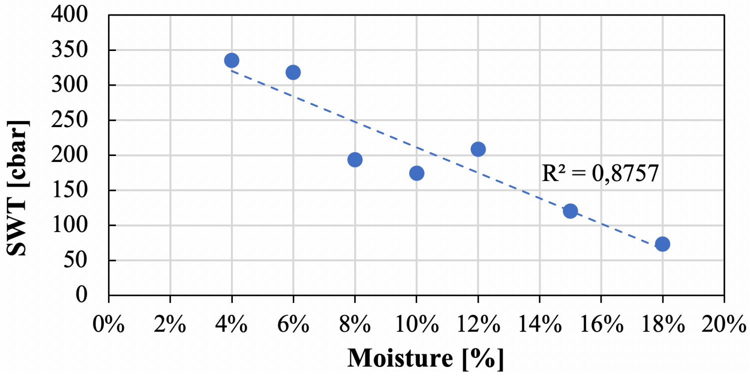


Fig. 6: correlation between SWT and moisture amount obtained using brick 1.

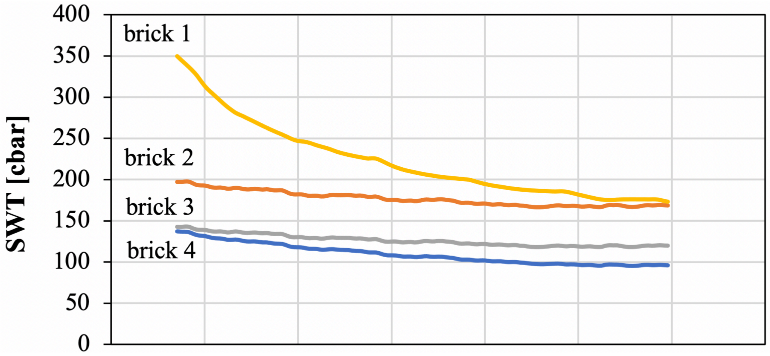


Fig. 7: SWT variation curves for the four different types of brick, at moisture content 10%. SWT is plotted versus time, thus showing the attainment of the equilibrium in the system brick+sensor.

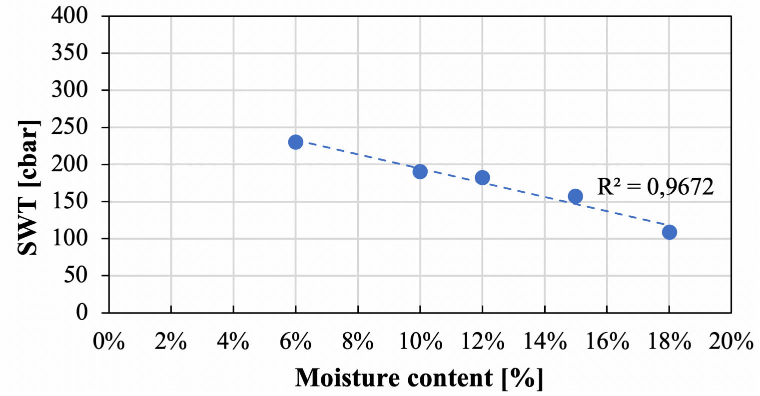


Fig. 8: SWT versus moisture content, obtained using brick 4 and performing the measurement at a constant temperature of 20°C.

Following the results obtained, a sensorized plug based of the use of brick 4 will be manufactured according to the scheme in Fig. 3 and used for further testing. The brick element of the plug will reach the equilibrium with the surrounding masonry in which it is inserted, while the sensor will always remain in contact with the same material.

Conclusions

The present paper represents a preliminary study aimed at the development of a sensorized ceramic plug to be inserted inside historic masonry walls for moisture monitoring purposes. The results obtained so fa are very encouraging, but several aspects need further investigation, such as the role of temperature, the role of soluble salts that are often present in buildings affected by rising damp and the kind of equilibrium which establishes between the ceramic plug and the surrounding historic bricks. All these aspects are currently under investigation within the MIMESIS project, also including a trial testing in-the-field, in two historic buildings in Italy.

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