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SCIENCE DIRECT
Building and Environment 41 (2006) 1372–1380
BUILDING AND ENVIRONMENT
www.elsevier.com/locate/buildenv

An operative protocol for reliable measurements of moisture in porous materials of ancient buildings

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Received 4 March 2004; received in revised form 5 May 2005; accepted 13 May 2005

Abstract

As moisture is the main cause or concause of decay of ancient building materials, a wide range of measurement techniques is presently applied for detecting its presence in structures. Nevertheless, the most common techniques often provide only qualitative results or not fully repeatable data, which is a severe problem when continuous monitoring of structures is required against moisture damage.

In this paper, an operative protocol for moisture measurement is proposed, which is based on the gravimetric method and provides true reliable data when periodical measurements must be carried out, particularly when assessment of dehumidification treatments, materials and technologies is required in ancient, historical buildings.

Keywords: Ancient buildings; Architectural heritage; Diagnostics; Moisture measurement protocol; Gravimetric method; Laboratory assemblies.

1. Introduction

Moisture is one of the main problems for both historical and new buildings [1], as it affects their hygiene, aesthetics and also structural safety. As a matter of fact, since the 1980s, the European Council Directive 89/106/CEE (21/12/88) enforces that building materials do not cause any moisture formation, raising occupants' health to the same level of basic requirements such as structural strength, fire safety, thermal insulation, etc.

Moisture can be conveyed into ancient buildings materials mainly by capillary rise, condensation, rainwater infiltration, leakage from water pipes and flooding. It therefore causes or worsens all the decay processes in building materials [2,3], such as rain-wash, freeze-thaw effects, migration and crystallisation of soluble salts [4], chemical and biological attack [5,6], corrosion of metallic elements and wind erosion [7].

Measuring moisture content in damp structures is the first step in order to find the actual source of moisture, to evaluate damp-proof systems and to make a really effective restoration work. Moreover, it allows to include in contract specifications quantitative requirements about the moisture content reduction to be achieved.

To this purpose, nowadays a wide range of techniques, either destructive or non-destructive, direct and indirect, etc., for investigating moisture content in buildings is available.

1.1. Indirect survey/measurement methods

Infrared (IR) thermography can detect damp areas in the structures due to their different temperature compared with the dry ones. Considerable efforts have been made to improve the accuracy of the information achievable by this technique: interference filters to eliminate the atmospheric attenuation effect due to air

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0360-1323/$ - see front matter
doi:10.1016/j.buildenv.2005.05.023

humidity and pollution [8], operative protocols for a correct choice of the weather and time for testing [9], measurement of the infrared radiation reflection from the surfaces (active thermography [10]). Despite these improvements, which anyway make this technique more and more attractive for a non-destructive, rapid and whole-scanning survey of historical buildings, a quantitative measurement of moisture is not achievable, due to the very different emissivity of dry construction materials [11] and, hence, the need of detailed case-by-case laboratory calibrations. A promising approach seems to be the use of wavelength-modulated infrared lights in active thermography [12], which allows to separate the reflection from moist and dry materials, but it appears to need further investigation. In any case, IR techniques provide information only about the hygrometric state of the thin materials layers just beneath the surface, strongly affected by the outdoor conditions and therefore strongly different from the internal materials conditions.

Measurement of the electrical properties of building materials on site is also well documented as a mean for determining their moisture. The electrical direct current (dc) resistance of a porous material, for example, decreases with its water content and its measurement is easy, cheap and quick to perform, but does not provide a reliable account of the moisture content in a building element, because the material's response is strongly influenced by factors other than moisture, i. e. temperature, dry materials electrical resistance and salts content, surface conditions, through which the measurement is usually performed by two pointed electrodes, either pushed on the material surface or driven in it (particularly in the case of wood), etc., thus measuring essentially only the moisture of the thin external layer of the material. Moreover, the electrical contact between the wall and the metal electrodes is quite variable, depending on the pressure exerted during the measurement, the contact area, the material roughness, etc. Materials conductivity can be investigated also by detecting the materials response to the propagation of electromagnetic fields generated through a transmitting coil [13], but the drawbacks of this technique are similar to the previous one.

Measurement of the alternate current (ac) dielectric properties of construction materials is widely used for detecting moisture content, since the dielectric constant of water is considerably higher than that of common, dry porous building materials. Impedance- [14], capacitance- [15] or permittivity- [16,17] based methods have therefore been reported, which normally use two electrodes simply pushed on the material surface: in these methods, the ac electrical field is often claimed to be able to penetrate the material up to about 7 cm. However, again the results may be affected by unknown and often unforeseeable factors, depending on the material nature and surface state, electrode/surface contacts and shielding, ac source frequency, etc. Even an appropriate laboratory calibration (far from being non-destructive) cannot assure a suitable results accuracy due to the strong heterogeneity of historical building materials and surfaces; hence, also these techniques can be used only for a preliminary non-destructive, qualitative survey.

Radar [18] and microwave [19] techniques to assess the dielectrical properties of structural materials at frequencies higher than the above quoted dielectric measurements have been reported. In microwave methods a very high frequency pulse technique for the reduction of the influence of the salts concentration in moist materials [20] and measurements of the attenuation of microwaves with moisture [21] were proposed; radar testing was used for the measurement of the transmission velocity of electromagnetic impulses through moist stone masonries [22]. Nevertheless, also in these cases, no quantitative results can be obtained, unless experimental calibration curves are determined, which requires direct investigation of each building material, of course by withdrawing samples, placing the sensors and so on. All these operations cannot be fully reversed and, therefore, accepted in architectural diagnostic assessment.

Other properties that are affected by dampness are the response of materials to either neutron scattering techniques [23] or nuclear magnetic resonance [24,25]. Unfortunately, the first method raises considerable safety provisions and the latter is still unsuitable for in situ applications due to the large size of instrumentation needed.

Determining moisture in a building element by measuring the air relative humidity (RH %) under equilibrium conditions in a sealed cavity drilled in the structure [26], in a sealed pocket, as suggested by BS 82101 and 53252 [27] or in a glass container where a material fragment is put [28], have also been proposed. The main drawbacks of this approach are that the results are temperature dependent (so this measurement must be jointly performed) and quantitative relationships between RH % and moisture content of the material must be assessed for each case (i.e., through investigation of materials nature and microstructure).

1.2. Direct measurement methods

The calcium carbide and gravimetric methods are widely regarded as the most reliable for a quantitative measurement of moisture content in building elements, by suitable sampling. Nevertheless, the first one, which can be performed on site, may involve some moisture loss during the samples drilling, crushing [29], handling and weighing, so systematically leading to underestimation of moisture content by 2–3 wt% [30]. Also the gravimetric procedure, which can be carried out both on site (by portable thermo-balances) or in laboratory (by oven drying) usually on material powders taken by mechanical drilling at a fixed depth in the building faces, can be affected by errors in sampling and samples handling.

The portable thermobalances, usually provided with data acquisition systems, are not very common for on-field applications yet. They can lead to errors due to poor experience of the operator (parameters setting, sample handling, etc.) or high sensitiveness of the balance (wind, slope and vibrations can often affect the results). Thus, the use of laboratory procedure on samples withdrawn from the building component should be always preferred, although it is surely more complex and time consuming than the portable on-site techniques. Two Italian NORMAL Recommendations [31], now available as UNI testing methods, suggest standard procedures in order to reduce the gravimetric method errors and many other efforts have been made for this purpose [32]. The use of low speed drilling for material sampling at the selected depth in the masonries is recommended in order to avoid samples heating and moisture loss by evaporation [33], as well as a shrewd sampling points choice and proper standardisation of the whole measuring procedure [34]. However, considerable errors can affect the direct methods, especially during periodical testing, as explained further in the following.

2. Moisture measurement requirements on materials of ancient buildings

Moisture measurements in ancient building materials must, therefore, be performed with higher accuracy than in the on site measurements procedures briefly reviewed above, to ensure its proper elimination or (at least) reduction by more or less effective anti-dampness provisions, to safeguard the ancient architectural heritage. Therefore, some general requirements for moisture measurement in historical buildings must be highlighted and sanctioned for meaningful and successful restoration works.

The first one is the need of accurate and reliable knowledge of the moisture content of the material, which can be obtained only by gravimetric method, withdrawing suitable and meaningful samples from the building faces and immediately sealing them in tight enclosures till the laboratory determination by oven drying.

The second basic requirement is the sampling procedure: it must be carried out deep into the structure, where the moisture is less affected by the outdoor conditions and more representative of true, average moisture content of the material. Sampling should be made at the same holes depth, but at different heights over the site plane, up to a point near or slightly above the so-called humidity "equilibrium line", particularly when anti-dampness techniques in historical buildings are to be evaluated (for 4–6 months or more by successive measurements, with reference to the outdoor/indoor microclimatic conditions). This requirement involves the basic issue of the repeatability of the performed measurements. Therefore, sampling must be repeated in the *same* brick, ashlar or zone of larger building elements, due to the great microstructural heterogeneity of historical building materials (e.g., masonry bricks, natural stones, etc.). Indeed, even adjacent building elements, such as masonry bricks or stone ashlars, can exhibit extremely different mass transport properties due to their far different microstructure, i.e., open pore distribution and average size, glassy and crystalline phases size and distribution, salt content, etc., of the sampled building material. Therefore, they may exhibit very different moisture content, thus preventing any comparison of the evolution of moisture content with time. In Fig. 1, the pore size distributions of some masonry bricks from the SS. Crocefisso Church in the Monumental Cemetery of Ravenna (1817), suffering huge damage by permanent rising humidity and needing therefore accurate monitoring as a function of time to evaluate different anti-dampness provisions, are reported as an example [35]. The outstanding difference among them is to be ascribed to the poor craftsmanship of the pre-industrial masonry bricks technology at the time of construction [36,37], systematically involving variable firing temperatures and atmosphere. A significant microstructural heterogeneity can also be detected in natural stones, due to the different location of the quarries, different sedimentary members, geological history, etc., as reported elsewhere [38–40].

The kind of sample to be measured is presently not considered at all for moisture content measurement of

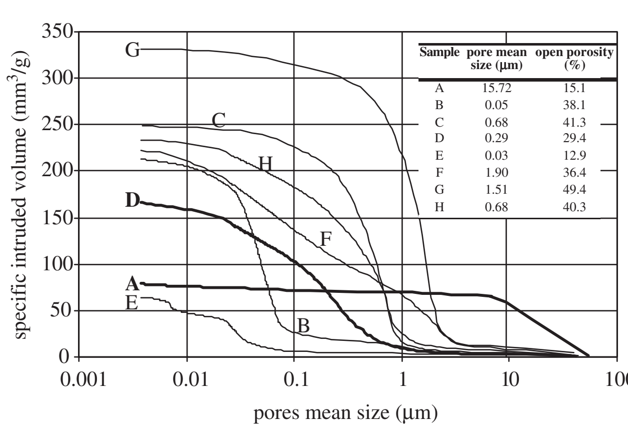

Fig. 1. Pore size distribution of some brick samples from the SS. Crocefisso church.

the building materials. In repeated measurements, it is usually considered fully satisfactory and meaningful to withdraw periodically the drilling powder residue remaining in the sampling cavity after drilling and to measure its humidity content. But one should consider that microstructure of a powder is very different from that of the solid from which it comes and this point will be dealt with later.

The third basic requirement is that the thermo-hygrometric conditions of the investigated building material must not be affected by the measurement itself. This is difficult to achieve, e.g., when many holes are drilled in a small area for sampling purposes. Furthermore, whatever is the sampling procedure, in repeated measurement the sampling holes must be kept sealed by a rubber stopper and a low modulus, hand mouldable sealing plastics (e.g., such as "plasticine") to tightly insulate the cavity from the outside environment and to keep the inside atmosphere in equilibrium with the moist material itself. Otherwise, the open cavity operates as a true drying channel, heavily disturbing the moisture content.

3. Experimental

In order to evaluate the whole gravimetric procedure for the determination of moisture content in the materials of ancient buildings (with particular reference to sampling), two experimental laboratory model assemblies were designed and constructed (*assembly1* and *assembly2*) using two kinds of commercially available masonry bricks (respectively *BR1* and *BR2*, supplied by Silam—Medicina, Italy, and RDB—Pontenure, Italy).

The masonry bricks of two different, current productions of normal size 25 × 12 × 5 cm were cut into smaller and modular parallelepiped elements and piled as shown in Fig. 2, in order to obtain models of walls at a laboratory scale, kept under continuous moisture rise from the bottom of the assemblies by lapping them with a constant 2 cm tap water level. Pieces numbering and approximate dimensions are shown in the same Fig. 2. Previous experimental tests on different masonry bricks were performed to individuate the surface–volume ratio of the assemblies which allowed to locate the so-called moisture equilibrium line (by visual inspection) at a level, below the assembly top, depending on the nature and microstructure of the masonry bricks investigated. The assemblies sizes and geometry shown in Fig. 2 ensured the feasibility of the investigation in a laboratory environment (temperature $T = 23-29\,°C$, RH = 30–50%).

In order to fulfil the requirements highlighted in the previous section, the use of *permanent sampling points* was simulated by drilling *permanent holes* in the

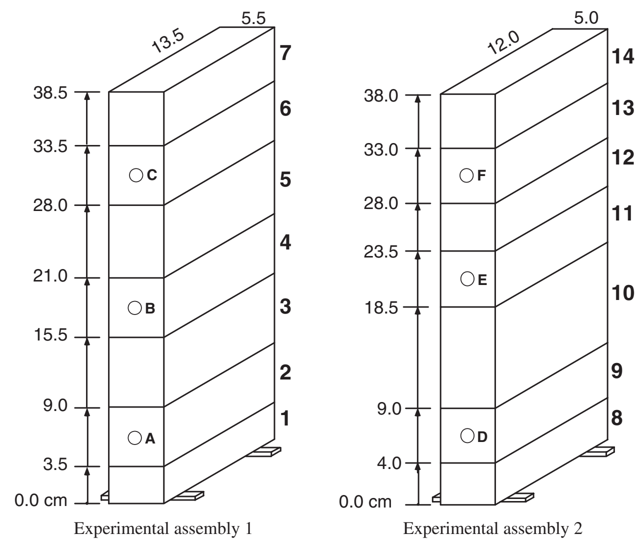

Fig. 2. The two experimental assemblies.

assemblies. In selected brick pieces of square section, holes were drilled with a diameter of 1.5 cm and depth of about 9 cm, i.e., 3/4 of the whole length of the pieces, sizes which were considered equivalent to those suitable for real scale monumental buildings (i.e., about 15–20 cm), where any destructive sampling must be controlled. The drilled pieces were located at approximately the same height of the two assemblies. The not-drilled pieces were kept randomly sized and distributed in both assemblies to reproduce the random sizes and distribution usually found in the wall materials of ancient buildings and to make the moisture rise as uniform as possible across the section and not affected on average by the holes presence in some pieces. To ensure the best contact between bricks and together the lowest resistance to moisture rise at the bricks contact interface, a powdered layer (thick about .5 cm) obtained by milling the *same* kind of brick of *each* assembly was put between the pieces. This ensures a continuous path for the capillary rising water as well as quick dismantling of the assemblies in order to measure the actual "true" moisture content of each piece.

Drilling powder and small brick fragments, coming from the same brick in which the hole was drilled (to ensure highest similarity with the chemical and physical properties of the brick type, and also microstructure for fragments), were put into each hole; the holes were then sealed with rubber stoppers and plasticine to ensure the attainment of the same thermal-hygrometrical equilibrium of the host brick in each assembly. The assemblies were kept lapped by tap water as previously quoted in the constant indoor laboratory environment at the above-described thermal-hygrometric conditions, until the rising water reached the expected, constant level (depending, of course, on the masonry bricks microstructure) and the whole capillary rise flow attained a

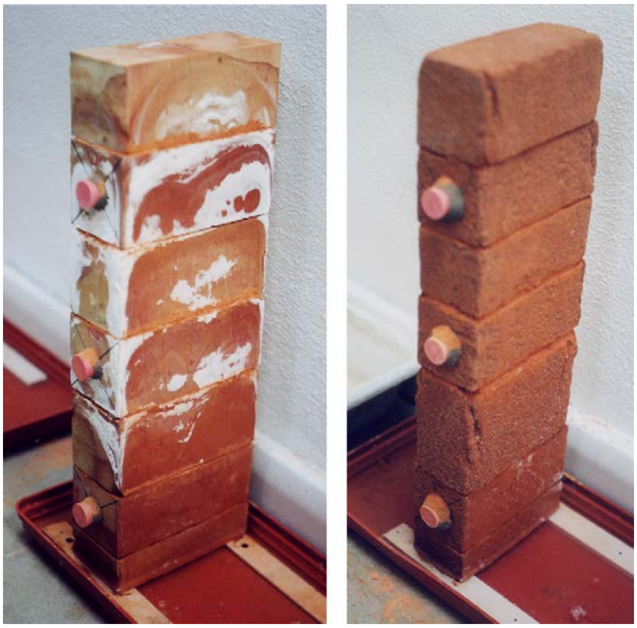

Fig. 3. The two assemblies in steady-state conditions.

steady state, revealed by the constant weight of the powder from the drilled holes at successive moisture content measurements (approximately, after two months) (Fig. 3). After that time the moisture content $M\%$ of the powders, fragments and bulk pieces (the latter by disassembling the assemblies) was measured after drying in an oven at 100–105 °C up to constant weight by a balance with an accuracy of 0.001 g, through the simple expression $M\% = 100 \cdot (W_m - W_d)/W_d$, where W_m and W_d are the moist and dry weights, respectively, as well as the temperature and relative humidity of the air inside the holes (by a thermal-hygrometric probe "Testo 635").

Pore size distributions of the samples BR1 and BR2 were determined (by mercury intrusion Porosimeter 2000 Carlo Erba with a Fisons Macropore Unit 120), as well as the total soluble salts and chlorides, according to the procedures of the Italian R.D. 16/11/1939, N. 2228 and ISO 9297, respectively.

4. Results and discussion

The two kind of bricks (BR1 and BR2) exhibit significant differences, as reported in Fig. 4 for the pore size distribution and Table 1 for the other chemical and physical properties. BR1 is much less porous than BR2 and exhibits a smaller pore mean size. Conversely, BR1 exhibits a higher salts content, as confirmed by the efflorescences displayed during the test (Fig. 3).

Table 2 shows the moisture content of each piece constituting the two assemblies (1–14 in Fig. 2): moisture obviously decreases with height. Assembly 2 is damper than assembly 1, according to the higher porosity of BR2 compared with BR1.

In Table 3 the moisture of the powders, fragments and relevant bulk pieces may be compared: the powders exhibit a much higher moisture content than the relevant bulk pieces, while the fragments exhibit essentially the same moisture content as the whole pieces, although systematically somewhat higher. These two effects may be easily explained on the basis of the microstructures of the different samples: (i) the powdered samples offer the largest specific surface area to water adsorption and capillary, large interstitial absorption between grains, so exhibiting a much higher water content than the bulk brick piece itself, (ii) on the contrary, the whole disassembled brick pieces exhibit a

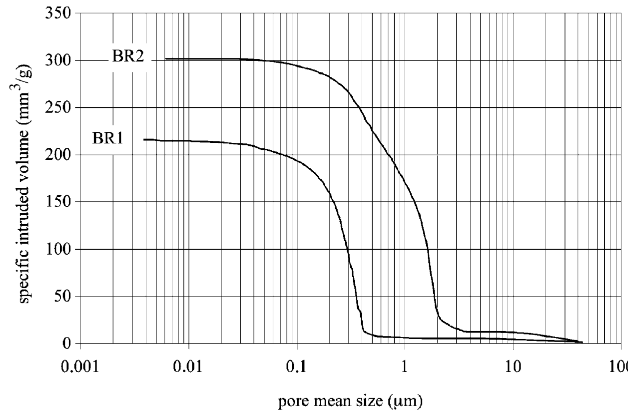

Fig. 4. Pore size distribution of the two bricks.

Table 1
Characteristics of the two kind of bricks BR1 and BR2

Brick	Characteristic compressive strength (N/mm^2)	Open porosity (%)	Density (g/cm^3)	Soluble salts (wt%)	Cl^- (wt%)
BR1	46.01	39.1	1.8	0.62	0.011
BR2	15.38	46.1	1.5	0.11	0.004

Table 2
Moisture of the brick pieces disassembled from the two assemblies

Assembly 1		Assembly 2	
Piece	M%	Piece	M%
1	20.78	8	29.39
2	20.14	9	28.63
3	18.43	10	26.40
4	18.21	11	26.90
5	17.24	12	25.45
6	16.63	13	25.28
7	15.67	14	24.33

Table 3
Moisture of the powders, the fragments and the relevant pieces of the two assemblies

Assembly 1				Assembly 2			
Hole	Height (cm)	Sample	*M*%	Hole	Height (cm)	Sample	*M*%
A	6.3	Powder	47.72	D	6.0	Powder	42.17
		Fragment # 1	21.21			Fragment # 1	30.66
		Bulk piece	20.14			Fragment # 2	30.86
						Bulk piece	28.63
B	18.0	Powder	30.54				
		Fragment # 1	18.82	E	20.8	Powder	39.64
		Fragment # 2	18.38			Fragment # 1	28.82
		Bulk piece	18.21			Fragment # 2	27.30
						Bulk piece	26.90
C	30.5	Powder	29.39				
		Fragment # 1	17.49	F	30.5	Powder	37.24
		Fragment # 2	17.82			Fragment # 1	26.54
		Bulk piece	16.63			Fragment # 2	27.03
						Bulk piece	25.28

moisture content averaged on both the internal and the external moist volume, an average that cannot be exhibited by the inserted fragments, due to their small size. The fragments withdrawn from the *same* brick must therefore be considered as the most representative of the bulk material moisture content, better than any other conceivable sample and sampling procedure.

It's noteworthy that, notwithstanding the small size of the fragments used (0.2–0.7 g), only slight differences in moisture content were detected among the different fragments within each hole (Table 3), thus confirming that the small sized fragments are well representative of the true, internal moisture content of the material, which is very important when moisture measurement is performed in monumental buildings.

In Fig. 5 the bulk pieces moisture content is plotted against that of the relevant powder samples: a relationship between them may be envisaged, but it clearly depends on the microstructure of the bricks. In fact, the powders drilled from the two bricks may have different grain size, due to the different brick hardness, hence giving rise to different and unpredictable interstitial capillary absorption. It may be again inferred that the measurement of moisture must be carried out on fragments and not on powders: it could be performed on powders only at the *first* test, i.e., straight after the holes drilling, accurately controlling that significant moisture loss caused by heating and/or sample handling does not occur.

The air temperature and the relative humidity RH inside the holes are reported in Table 4, together with those of the room environment. In Fig. 6 the bulk pieces moisture content is plotted against the air humidity inside the relevant holes: a relationship might be envisaged, but it is different for the two assemblies, as it depends on the thermodynamic equilibrium between the water content of the brick and the relevant humidity content of the air, within the closed up holes, and the

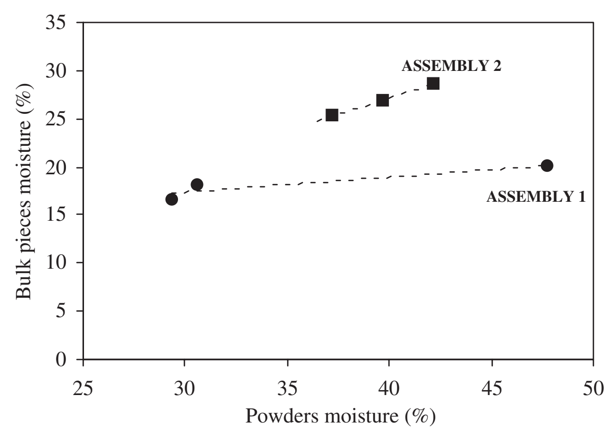

Fig. 5. Moisture of the bulk pieces vs. that of the relevant powders.

Table 4
Temperature (T_i) and relative humidity (RH_i) of the air inside the holes and relevant environmental temperature (T_e) and relative humidity (RH_e) during measurement in Table 3

hole	RH_i (%)	T_i (°C)	RH_e (%)	T_e (°C)
A	94.9	22.0		
B	95.1	23.6	55.5	24.4
C	91.4	24.2		
D	97.6	19.0		
E	97.1	18.8	44.4	23.2
F	94.7	20.7		

brick's microstructure. Of course, in steady-state conditions the humidity content of the air should be very near the saturation one at the assemblies temperature, as also seen in Fig. 6. However, it is usually not possible to find such a relationship between thermal-hygrometric parameters within the cavity and moisture content of the material during a normal diagnostic survey on a building, due to the building material heterogeneity. The relative humidity measurement can only help a preliminary indication about the walls dampness: indeed, assembly 2, whose material is more moist than that of assembly 1, shows a higher internal relative humidity.

The investigated and proposed on-site system for moisture content measurement in actual ancient, historical buildings, is finally outlined in Fig. 7. The hole cavity must be kept sealed with a rubber stopper and plasticine (Fig. 7) and the fragment extracted and measured only after the steady-state conditions are attained in the fragment material, usually after at least one month after the fragment insertion in the hole, in the authors' experience.

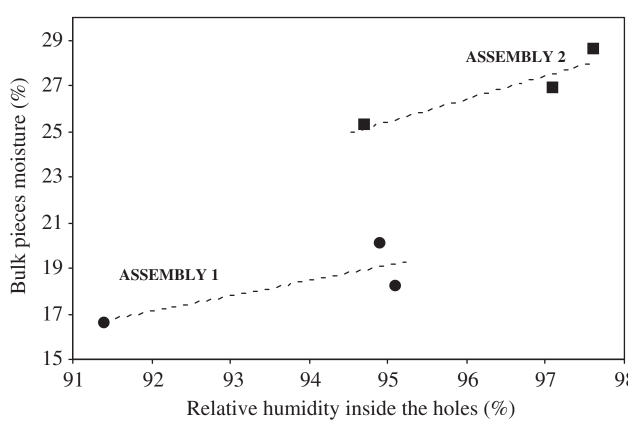

Fig. 6. Moisture of the bulk pieces vs. relative humidity inside the relevant holes.

As largely experienced in actual ancient and monumental buildings monitoring, a significant survey of the building should be made by at least three different heights (or more, depending on the intensity and level of the rising moisture as pointed out from the equilibrium line) for all the wall face points considered meaningful and important for the testing: the testing points could first be located at a height of 20–30 cm from the ground level, the second in the damp area (about half of the maximum rising height) and the third in the dry area, just above that line. As to the hole size, a diameter of 15–20 mm and a depth of 15–20 cm, depending on the bricks/ashlars size and the wall thickness, are suitable for monumental buildings, where any destructive action must be controlled.

5. Conclusions

The operative protocol discussed and proposed above, based on the sketch of Fig. 7, provides reliable and reproducible data on moisture content measurement in the materials of ancient architectural structures and at present is successfully in use in several historic buildings, both Italian (St. Marco Basilica in Venice [41], Palazzo Pio at Carpi [37], St. Francesco church at Correggio, St. Luca and Alemanni porticoes in Bologna [36]) and Maltese (St. Caterina d'Italia church in La Valletta [40]).

The main features of the protocol are the following:

- quantitative, reliable and accurate data are obtained via the gravimetric method; of course, attention must be paid to the samples storage in air-proof containers, oven temperature control, balance accuracy, etc.;

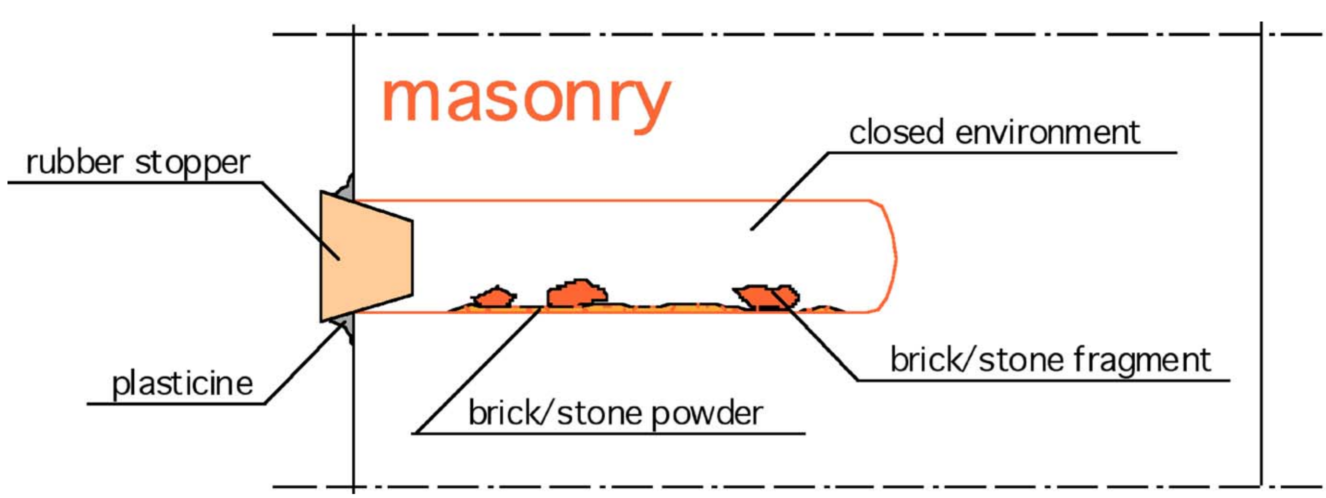

Fig. 7. Hole cavity for reliable moisture content determination of ancient building materials (schematic).

- all the data are fully comparable in the case of repeated measurements, as assessed by author since 1994 on ancient restoration yards;
- fragments can be used indefinitely, as they can be reinserted into the hole cavity they were extracted from after each measurement, which returns the dealt with fragment perfectly dried;
- moisture content is measured deep into the wall, where the thermal-hygrometric influence due to the external environment is negligible; this ensures that it faithfully represents the actual material situation;
- a very modest action on buildings is required, thanks to the small size of the holes and fragments;
- errors related to the moisture loss during drilling can be avoided, if the measurement, after the first one, is performed always on the fragments;
- the hole drilling provides powdered samples suitable for several initial chemical–physical analyses (salts content determination, X-ray diffraction, etc.), which helps in possible interpretation of the moisture effects on the building materials properties and their decay;
- the procedure is easy to perform and does not require expensive equipment: only a commonly equipped laboratory must be available.

These advantages make this method suitable particularly when the effectiveness of ancient buildings dehumidification systems must be evaluated.

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