Engineering Failure Analysis 45 (2014) 185–203

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Experimental investigation on bricks from historical Venetian buildings subjected to moisture and salt crystallization

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ARTICLE INFO

Article history:
Received 20 March 2014
Received in revised form 21 May 2014
Accepted 25 June 2014
Available online 5 July 2014

Keywords:
Brackish water
Brick's compression strength
Environmental actions
Moisture
Salt crystallization

ABSTRACT

The research presented in this paper investigated the mechanical behavior of bricks subjected to moisture and salt crystallization, and aimed at determining the mechanical degradation of bricks due to these environmental factors.

Compression tests were performed on bricks removed from an historical Venetian building. The paper presents the experimental campaign and the results. The analysis of the experimental results provided novel information about the effects of moisture and salts on the compression strength of bricks. In particular, the experimental results demonstrate that moisture significantly reduces the compression strength of a brick; the greater the moisture content the lower compression strength, all other condition being equal, in particular salt concentration inside the brick. Moreover, the experimental results demonstrate that salts together with moisture significantly reduce brick compression strength, while salts without moisture increase brick compression strength. However, the crystallization of these salts can cause subflorescence and efflorescence inside the bricks, which eventually reduce the compression strength of the bricks and the masonry.

The paper provides a discussion on the results that extends the outcomes to any masonry building subjected to brackish water or tides. The conclusions are devoted to safeguarding and conservation of masonry buildings that suffer from humidity and salt crystallization.

1. Introduction

Venetian buildings have to endure the lagoon environment, which is aggressive since the water of the lagoon is brackish (dissolved salt content) and the lagoon is subject to high variations of water level (daily tidal cycle).

Salinities in the Venice lagoon were recorded from May 2005 to February 2007, and chloride concentrations in pore fluids were measured up to 1.50 m [1]. The measures showed that salinity in the Venice lagoon is significant, as well as its variations during the seasons.

The cycle of the Venetian lagoon tide has a period of approximately 21 h and 30 min, and a difference between the high tide and ebb tide (not the following ebb tide, but the difference between the high waters and the low waters) that may surpass 1.70 m and that has an average value greater than 0.60 m. The combination of brackish (briny) water and tides (high and low water) of the Venetian lagoon was modeled [2]. The simulations confirmed that this combination of conditions causes the Venetian buildings to withstand severe environmental actions.

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http://dx.doi.org/10.1016/j.engfailanal.2014.06.019
1350-6307/

1.1. Sources of damage in bricks: moisture and salt crystallization

It is well known that the vast majority of the Venetian buildings are historical and most of them have vertical structures made of brick masonry.

The bricks below the sea level are exposed to the direct contact with the water, which causes damage to the masonry structures [3,4]. However, this is not the only source of mechanical damage to masonry; there are also the water-soluble salts contained inside the bricks [5–10], which are a major source of mechanical damage.

The manufacturing process causes pores to develop in bricks, as a consequence of the spaces between the grains of sand, which create the conditions for water infiltration. Consequently, during high tide, the water of the lagoon infiltrates into the bricks submerged by the high water [2,4,9–11] and increases the moisture content of the bricks [12–16].

The number and size of the pores inside a brick depend not only upon the size of the grains, but also upon the manner in which they are packed, the temperature they are baked, and the type of cure they are subjected to. Venetian bricks were handmade and this type of manufacture process caused the bricks to be highly porous [7]. Since in handmade bricks the porosity is very high, the water can infiltrate easily into this type of bricks.

Water infiltration renders the salts contained inside the bricks into a soluble solution [17]. In the case of Venetian buildings, furthermore, the water of the lagoon contains the same salts as the bricks [6,7]. Therefore, water infiltration adds these salts to those contained inside the bricks [9], which results in a solution with high salt concentration.

Salt molecules in the solution meet up and interlock. As they do so, they fit together, arranging themselves in a lattice structure, thus creating a crystal nucleus. However, this condition is both unstable and dependent on the boundary conditions. In fact, as more molecules find the nucleus and connect to each other, the nucleus grows too large to remain in the solvent condition and falls out of the solution. Hence, it crystallizes [5,8,17–20], especially when the salt concentration is high. Moreover, during the ebb tide (or during the mean sea level), as the moisture evaporates [21–23], the amount of water present can no longer preserve all the salts in solution and the salts will need to precipitate out. Also in this case, salts crystallize.

Moreover, in the case of Venetian bricks, whose porosity index is high since they were handmade, the water can find easily paths for the soluble salts to migrate through to the surface where the moisture can evaporate [17].

Crystallization deposits crystals of salt below the surface of the bricks. Crystallization within the pores of the brick is called “subflorescence” [24].

According to the above description of the salt crystallization phenomena, Venetian buildings suffer significantly from subflorescence, since the daily variations in water levels are high for a large proportion of the year [1,2]. Thus, the portions of masonry subjected to high and low water are equally significant, which continuously changes the level of humidity present inside the bricks, and leads to subflorescence.

Subflorescence can create pressure that will eventually induce cracks inside the brick, defoliation, localized crumbling or spalling of the brick face [9,20,25–27]. Spalling is a form of deterioration where small fragments of brick break away from the masonry system (detachment of superficial chips of material). Spalling may dislodge individual masonry units.

Another boundary condition whose change influences the salt molecules in the solution is the difference in temperature between the interior and exterior of the building. The heat inside the building (especially during the winter) moves outward and drives the moisture in front of it [4,11,14–16,23]. When the water–salt solution reaches the exterior wall surface, the cold and dry air evaporates the water, leaving the salts as a white crystalline growth on the surface. Hence, as the moisture evaporates, it deposits soluble salts on the surface [17–22] and the building will exhibit white powder due to the accumulation of mineral salts on masonry surfaces.

Crystallization in a film of solution on the exterior surface of the body is called “efflorescence” [5,24]. Efflorescence on the surface of the masonry obviously mars the appearance of the building, since it causes a variation of the superficial coloration of the bricks. In the Venetian buildings, sometimes, the accumulation is brown, green or yellow. Moreover, efflorescence causes the brick to become incrusted with crystals of salt.

Regarding the mechanical aspects, efflorescence is often believed to be harmless, since it is believed that it does not affect the coherence and endurance of the building materials. Conversely, not only can efflorescence indicate the presence of subflorescence, but it may cause spalling of the brick surface [24–27]. Thus, efflorescence is harmful.

Ultimately, crystallization of salts is a common cause of mechanical damage in bricks. On the contrary hydraulic lime mortar, in particular, hydrated lime used in the mortar of historical buildings, does not contribute sufficiently towards the soluble alkali sulfates necessary for subflorescence and efflorescence to occur [28]. In addition, the voids in hydrated lime mortars are a small number; thus, there is little volume for capillary flow of any solutions through the hydraulic lime mortar [9,11–17,22,28].

The above description of salt crystallization phenomena concentrated on the Venetian bricks. However, these phenomena are applicable for all the masonry structures that are subjected to tides and/or brackish water (i.e., water with more salinity than fresh water but not as much salinity as seawater, which is the case of lagoons and estuaries). In these masonry structures, subflorescence and efflorescence grow much faster than average. In masonry structures subjected to large tidal excursion the portions of masonry subjected to high and low water are significant. In masonry structures subjected to brackish water, the water in direct contact with the masonry contains the same salts as the bricks, which the infiltration of water add to the salts contained inside the bricks. In the case of handmade bricks, the water can infiltrate easily and the moisture can evaporate easily, which further increases the growth of subflorescence and efflorescence.

Accumulated moisture within the bricks may also be subjected to freeze–thaw cycles. In the case of Venice this is not so, but it may occur in other lagoons or in bricks subjected to brackish water. The consequent expansion and contraction of trapped water can cause a series of harmful effects on the bricks, which include local crumbling, cracks, spalling, flaking, peeling, exfoliation or delamination [3].

1.2. Construction technique with brackish water and tides

Venetian architects, master craftsmen, masons and builders were capable of designing and constructing buildings that could withstand the severe actions of the lagoon. Above all, they provided the buildings with the means to cope with moisture and tidal change, as well as to resist the loads.

The first problem to solve was that the soil was soft, since the superficial soil layers were composed of silt and clay. Hence, they supported foundations on pile groups consisting of vertical piles embedded into the soil (driven into the ground in situ), up to reaching the deep soil layers, which are relatively strong (Fig. 1a).

Then, they constructed a pile cap on top of a group of foundation piles to evenly accommodate the building that the piles had to carry (Fig. 1a). The pile caps consisted of timber board, called "*madieri*".

The base of the building that rested on the madieri was made of normal bricks. These bricks were covered with special waterproof clay, called "*tera da savon*" (in Venetian vernacular), which prevented contact between the masonry and the water of the lagoon. The masonry walls of the building were raised onto this basis.

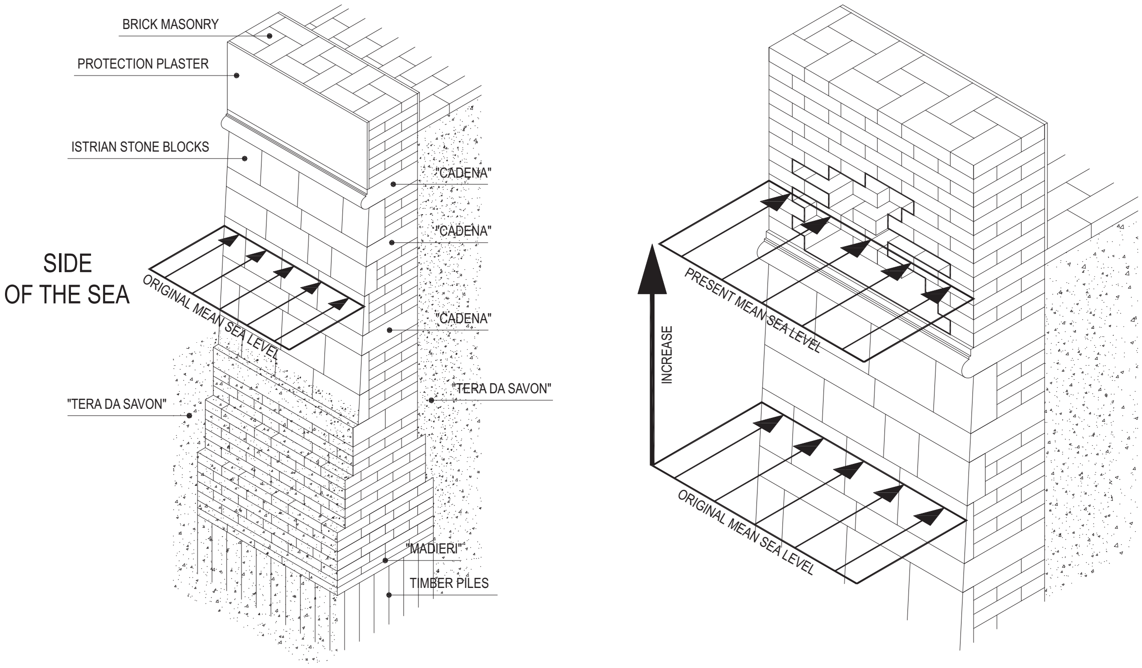
Moreover, a vertical layer made of Istrian stone blocks was placed on the side of the walls facing the canal, which prevented direct contact between the masonry and the water of the lagoon (Fig. 1a).

Some continuous courses of Istrian stone blocks, called "*cadene*", were placed above the middle see level, in order to create some waterproof layers that protected the upper walls from the rising moisture (Fig. 1a).

Finally, hydraulic lime plaster was spread onto the upper part of the walls, to protect the walls from the aggressive atmospheric agents.

The Venetian construction techniques have been a viable means of protecting the buildings from brackish water and tides. Unfortunately, due to the sea level rise, the water of the canals has often exceeded the upper level of the Istrian stone block layers, in the last decades (Fig. 1b). Thus, the bricks have frequently been in contact with the water of the lagoon. As a result, the condition of many Venetian buildings is severely degraded.

Part of the degradation is also due to a natural aging of buildings materials, which the construction techniques have delayed but eventually cannot avoid. However, a significant fraction of the Venetian buildings is subjected to high moisture content in the form of trapped water, and salt crystallization in the form of significant subflorescence and efflorescence. This is the main source of damage of the Venetian buildings [29].



(a) (b)

Fig. 1. Foundation system of historical Venetian buildings. (a) Conformation of the base of the vertical structures of the building. (b) Sea level rise during the centuries.

Masonry portions that suffer from trapped water and crystallization of salts are often restored by removing the salts and reducing the content of water trapped inside the bricks (Fig. 2). In Venice, this restorative result was mostly obtained using three techniques [30–32].

The first technique is to spread a layer of cellulose paste of palygorskite (attapulgite) onto one side of the wall and to clean the surface of the other side with water propelled at quite high speed (hydrocleaning) [12,16,20,29,30,33] (Fig. 2a). The surface of the wall can also be cleaned by embedding some pipes into the wall (Fig. 2b). In so doing, washing also reach the depth of the wall.

The second technique consists of installing physical and chemical barriers at the base of the wall together with a drainage system [3,11,14,29,30]. The physical barrier is obtained either by placing impermeable plates onto the base of the walls (Fig. 2c) or replacing the existing bricks with new bricks (Fig. 2d). In both the cases, the existing plaster is replaced with a macroporous plaster (Fig. 2f), which resists moisture rising. The chemical barrier is obtained by the injection of specific resins into the walls (Fig. 2e). These resins prevent the adhesion of the molecules of water at the base of the walls [8,10,15,21]. Also in this case, the existing plaster is replaced with a macroporous plaster [30,33] (Fig. 2f).

The third technique is electro-osmosis, which generates a magnetic field between the base of the wall and the ground by means of some series of electrodes having polarity sufficient to repel the water (Fig. 2h) [31,32].

1.3. Space-saving and weight-saving masonry structures

While the skeletal structures have only one function, namely to support the dead and live loads, masonry walls have multiple functions. In fact, not only do masonry walls support the weight of floors and roofs, but also they form the periphery of the building (exterior walls) and rooms (interior walls). Therefore, while the cross-section of a skeletal structure is proportional to the dead and live loads that it has to resist, the cross-section of the walls is also dictated by the area of the building that they have to surround and by the spaces that they have to divide or enclose. Often, the cross-sections that are necessary to shelter the building and to separate one internal area from another are more than enough to carry the dead and live loads of the building. In these cases, the masonry walls that satisfy the architectural requirements also satisfy the static requirements (but not necessarily the seismic requirements).

Moreover, historical buildings did not have any heating and cooling systems, and thus the walls also had to provide the insulation needed in cold weather and hot weather. To insulate the building, extra-width and/or extra-thickness were often needed. Hence, the walls of historical buildings are often largely oversized from the structural point of view.

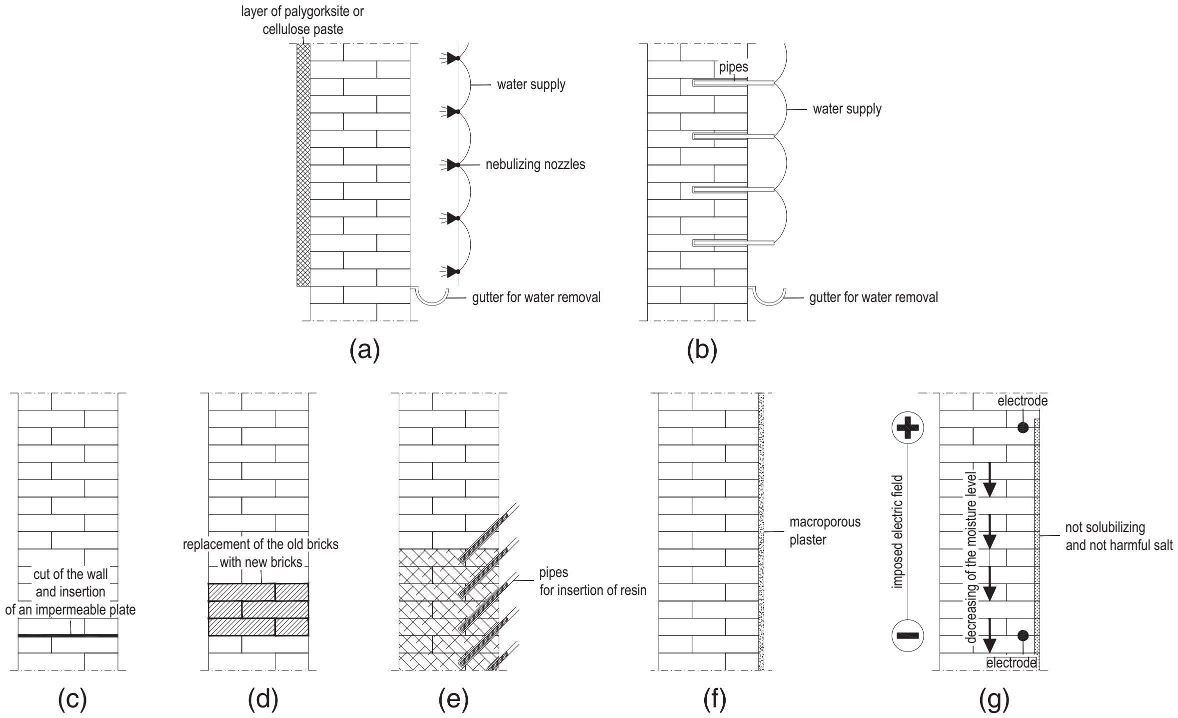


Fig. 2. Technologies to improve the living conditions of a building. (a and b) Salt removal. (c and d) Reduction of the moisture content by means of physical barriers. (e) Reduction of the moisture content by means of chemical barrier. (f) Replacement of the existing plaster with a macroporous plaster. (g) Electro-osmosis technology.

However, the above-described oversizing of masonry walls met an exception – namely, when the masonry buildings were located in sites where the space available was particularly limited or where the soil was particularly soft. Venice met both these conditions. Thus, the Venetian buildings were built so that the vertical structures occupied as little space as possible. Hence, Venetian buildings were constructed using space-saving and weight-saving masonry vertical structures.

Accordingly, Venetian buildings were composed of relatively thin or perforated walls and included many columns. In many Venetian buildings, therefore, the masonry structures are strictly sufficient to carry the loads.

It follows that, while typically in masonry structures compression stresses are drastically lower than compression strength (i.e., crushing strength), in the Venetian buildings compression stresses may exceed compression strength. Thus, while crushing is not a typical mode of failure in masonry structures, it is a mode of failure that has to be assessed in Venetian buildings. This also holds true for the buildings all around the world that, for any reasons, required space-saving and/or weight-saving masonry structures.

2. Research significance

The increase of moisture and crystallization of salts results in physical modifications and mechanical degradation of the bricks. The treatments to remove moisture (e.g., drying) and salts (e.g., brick-washing), result in other modifications; e.g., the stiffness of the brick when the pores are empty is lower than when the pores are filled with trapped water and salts.

Since the structural behavior of the masonry also depends on the mechanical behavior of the bricks [35–38], these modifications and degradations affect masonry buildings. Thus, structural analysis of existing building has to consider the effects of moisture and salt crystallization on the mechanical behavior of the bricks, in particular on the strength [39,40].

Hence, structural safety of Venetian buildings is unfavorably affected by two factors – namely, the original safety coefficient against masonry crushing was often slight (see Section 1.3), and moisture plus salt crystallization may have further reduced the safety coefficient (see Section 1.2). Of course, these factors do not affect only the Venetian buildings, but also some other buildings in other locations all around the world.

Considering this, it is essential to know the effects due to moisture and salts on the compression strength of masonry. In literature, important results are available on this subject matter (see references), but despite this there was found to be a shortcoming of information on structural damage of masonry subjected to environmental factors. In particular, the literature provided a rather ambiguous picture about the behavior of masonry subjected to moisture and salt crystallization. In fact, the literature provided fundamental information about the effect of moisture and salt crystallization on the life span of bricks, but little information on how these actions may modify the mechanical behavior of bricks, in particular the strength.

In the field of existing masonry buildings, hence, there existed one important unresolved problem that impinged on all the structural analyses – namely the mechanical parameters of masonry with a close relationship with brackish water and/or tides. That problem encompasses some cities and towns in the World, which includes Venice, where it is critical.

The scientific literature also gave an ambiguous picture about the mechanical effects of the techniques that remove moisture and salts from bricks, whether they improve the strength or not. That gap leads some practitioners to claim that those techniques improve the living conditions of the building but worsen the mechanical properties of the walls.

With the new design and assessment procedures for existing building included in the last generation structural codes issued in Europe [34], the problems must now be solved. In fact, these procedures require reaching at least a minimum level of knowledge of the analyzed building, which includes the mechanical parameters of masonry. Thus, the modifications of the mechanical parameters of bricks due to moisture and salt crystallization have to be identified when assessing safety of existing buildings.

This paper's aim was to fill the above identified gap; activity was directed at analyzing the behavior of bricks subjected to moisture and salt crystallization, and carrying out research targeted at reducing the incidence of failure due to degradation of engineering materials.

3. Theoretical relationships for masonry compression strength

Compression strength of masonry depends on many factors [35–45], which include the mechanical characteristics of the components (compression strength, elasticity modulus, and hygroscopicity of the blocks and mortar [36–38]), and the relationships between the components [34,35,39,41] (the texture, and the ratio between the dimensions of the individual masonry unit and mortar joints [37]).

Literature demonstrates the existence of empirical relationships between the masonry compression strength and the compression strength and geometric characteristics of the components. There are expressions that provide the compression strength of masonry f_M (masonry ultimate stress) [35–39] known the compression strength of either the block f_b (i.e., brick ultimate stress) or the mortar f_m (mortar ultimate stress):

$$f_M = \sqrt{f_b} \tag{1}$$

$$f_M = \sqrt[3]{f_m} \quad \text{or} \quad f_M = \sqrt[4]{f_m} \tag{2}$$

The units of (1) and (2) are N/mm^2. There are also expressions that provide f_M known both f_b and f_m (units in N/mm^2) [35–39]:

$$f_M = 0.7\sqrt{f_b}\sqrt[3]{f_m} \tag{3}$$

$$f_M = \frac{f_b}{6} + \frac{\sqrt{f_b + f_m}}{4} - \frac{f_m}{20} + 1.4 \tag{4}$$

$$f_M = (1 - 0.8\sqrt[3]{\alpha})f_b \quad \text{if } f_b < f_m \quad f_M = (1 - 0.8\sqrt[3]{\alpha})[f_m + 0.4(f_b - f_m)] \quad \text{if } f_b > f_m \tag{5}$$

In Eq. (5), α is the ratio between the thickness of the vertical mortar joint and the height of the block. Eqs. (1)–(5) apply to both brick and stone masonry. Nevertheless, there are also expressions that differentiate the type of block [35–39]:

$$f_M = \left(\frac{2}{3}f_b - f_0\right) + \delta f_m \tag{6}$$

In Eq. (6), f_M is the ultimate stress of the block (units in N/mm^2), f_0 is equal to 0 for brick masonry, 0.5 N/mm^2 in the case of stone masonry with squared blocks, and to 2.5 N/mm^2 in the case of stone masonry with not squared blocks. The coefficient δ is equal to 0.1 in the case of brick blocks and 0.5 in the case of stone blocks.

Eurocode 6 [34] includes an expression that provides the compression strength of masonry f_M combining the compression strength of the brick f_b, and mortar f_m (in N/mm^2):

$$f_M = k f_b^{0.65} f_m^{0.25} \tag{7}$$

The coefficient k, whose units are (N/mm^2)$^{0.10}$, takes into account the type of blocks, whether bricks or stones, and the ratio between the block's width and masonry's thickness. The coefficient k is provided at point 3.6.2.2 of Eurocode 6.

3.1. Venetian environment

Whether or not Eqs. (1)–(7) hold true for Venetian masonry has been investigated and some scientific contributions are available in the literature [3,6–9,11,26,27,46]. In [46], in particular, Eqs. (5) and (7) were applied to some Venetian masonry structures. Both the state-of-the-art review and the case studies presented in [46] confirm that Eqs. (1)–(7) also hold true for masonry structures subjected to brackish water and tides, in particular for masonry structures of Venetian buildings provided that the strength values that are used in the formulas account for the mechanical degradation.

The above result demonstrates that research on the mechanical effects of moisture and salt crystallization on Venetian masonry has to focus on the effects of these factors on the strength of the bricks. Once these effects are determined, compression strength of masonry structures subjected to brackish water and tides can be obtained by using either Eqs. (1)–(7).

4. Experimental campaign on Venetian masonry bricks

This section describes the experimental campaign – planning, method, and approach – designed to determine the effects of moisture content and salt concentration on the compression strength of Venetian bricks.

The experimental campaign required two steps, since the test methodology that was initially used to test the bricks led to unsatisfactory results. In order to improve the accuracy of the experimentation, a second step was carried out, which overcame the inconveniences of the first step.

More specifically, initially the experimental campaign aimed at testing the bricks in the exact condition that they had been removed from the building. In so doing, however, the compression strength values of specimens coming from the same brick exhibited very high variance. The reason for this variance was explained once moisture content and salt concentration were measured in each individual brick. These measures were very spread out from each other. Thus, the large variance of the compression strength of the specimens coming from the same brick was attributed to the large variance of moisture and salt within the brick.

The large variance invalidated the experimental results, since it was impossible to associate a unique value of moisture content and salt concentration to a masonry unit. Thus, the compression strength values of a brick could not be associated to any moisture and salt condition of the brick.

The large variance of the moisture content and salt concentration within the masonry unit, on one hand, was a result of the research; on the other hand, however, it was an inconvenience that needed to be overcome.

Therefore, the experimental campaign proceeded with a second step. In the second step, the limit values of moisture contents and salt concentrations found in the first step were reproduced artificially in the specimens. In so doing, the moisture content and salt concentration of each second-step-specimen were known and constant over each brick. Hereafter, only the second step is considered.

4.1. Specimens

The test bricks were removed from the masonry walls of an historical Venetian building – namely, *Gussoni-Grimani* palace (Fig. 3). This is a brickwork building, whose bricks were handmade.

Gussoni-Grimani palace, which was built between 1548 and 1556, has six stories; it is located in Sestiere di Cannaregio (Fig. 3a).

The lowest story of the building, which is approximately at the level of the sea, was formerly used to embark and disembark people on boats, to load and unload merchandise and as storerooms (Fig. 4). Above the lower story, there is a low-ceiling story, which is the first mezzanine (entresol). The third and fifth stories of the building are the noble stories, which were used in part for formal entertaining and in part for private residential. Between the noble stories there is the second mezzanine. Above the second noble story there is the attic (Fig. 4). The plan of the building includes a central rectangular atrium (Fig. 4).

Two sides of the building overlook the canals; the façade overlooks *Canal Grande* (Fig. 3b), and the Est-side overlooks *Rio di Noal*.

The authors chose this building since it included all the possible relationships with the lagoon. In fact, part of this building had a direct contact with the lagoon water and no measures had been taken against moisture and salt crystallization, apart from the original construction techniques. Conversely, the other part of the building did not have any contact with the lagoon water. Moreover, *Gussoni-Grimani* palace had not undergone significant alterations during its history; thus, all the walls were composed of the original bricks. Finally, the building was being subjected to restoration work; thus, to remove bricks from the walls would not have damaged it and the information provided by the experimental campaign would have helped the restoration design.

The bricks were removed from the walls at the lower level, which were subjected to moisture and salt crystallization more than the walls at the other levels. The bricks were removed from walls facing the canals and walls that did not have direct contact with the canals. More specifically, the bricks were removed from four masonry walls (Fig. 5) – namely, an internal wall of the atrium (area A), a wall overlooking the *Rio di Noal* (area B), an internal wall of a room connected to the atrium (area C), the façade (Fig. 3b) overlooking *Canal Grande* (area D). Two bricks were removed from each wall (Fig. 6a and b).

The bricks of these walls exhibited a considerable state of degradation, and some of them were particularly soft. In order to identify bricks that were compact enough to extract non-disturbed specimen, a sclerometric analysis was initially performed (Fig. 7).

Ultimately, eight bricks were removed from the walls of the building (plus some bricks that were discarded). The bricks that had been removed were numbered with an alphanumeric index (Table 1). The alphabetic part referred to the area where they had been removed from (Fig. 5) – namely A, B, C or D. The numeric part of the index identified the brick (Table 1; Fig. 8) – namely, 1 or 2.

Then, cylindrical specimens were extracted from the bricks. A core drill (with diamond impregnated bits attached to a core barrel) was used to obtain the cylindrical core specimens. The core drill extracted up to 14 cylinders of material from each brick that had been removed from the wall.

Seventy-seven specimens were extracted from the eight bricks (Fig. 9). Also the specimens were labeled with an alphanumeric code, which was that of the brick they had been extracted from and another progressive number that identified the specimens extracted from the same brick (separated by underscore). The specimens that were tested are shown in Table 1.

Each core was drilled perpendicularly to the surface and at least 7.5 mm away from the edges (Fig. 9). Then, the test specimens were provided with smooth, parallel ends, by using a saw for brick (with diamond cutting edge) that performed smooth cutting and slicing. Both the core drill and the saw were capable of removing and cutting cores without introducing

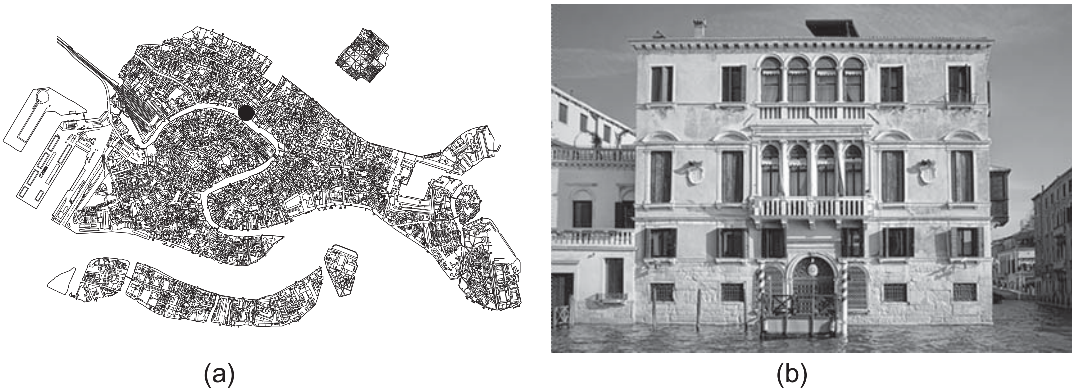

(a) (b)

Fig. 3. Historical Venetian palace where the bricks were removed from. (a) Localization of *Gussoni-Grimani* palace in Venice (Italy). (b) Façade of the *Gussoni-Grimani* palace, which overlooks *Canal Grande*.

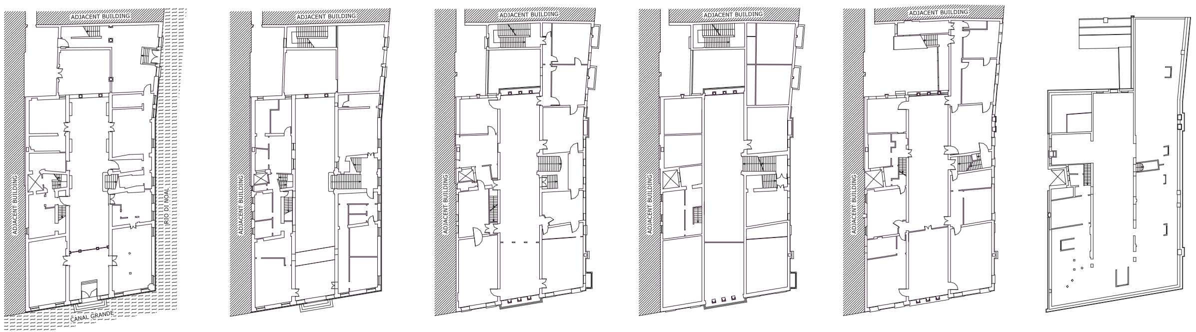


Fig. 4. Stories of the *Gussoni-Grimani* palace. The lower story is at the mean sea level. The second mezzanine does not have any window that overlooks *Canal Grande* (Fig. 3a), i.e. the windows of this story are at the other three sides of the building.

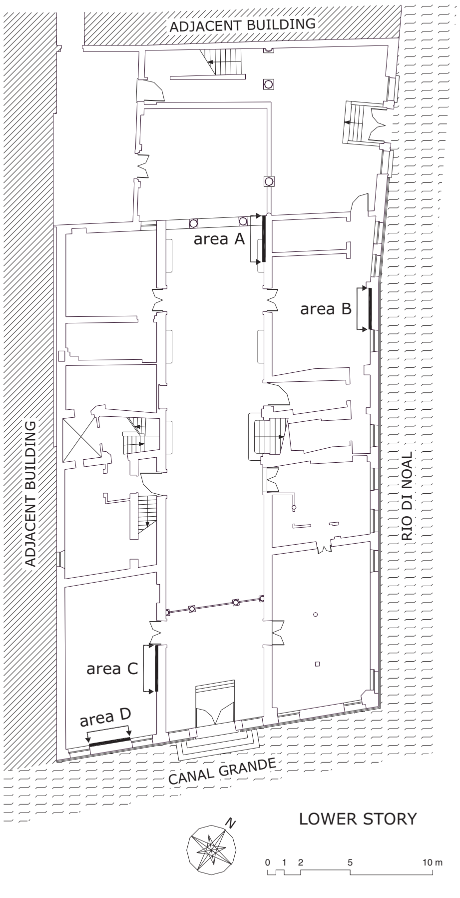


Fig. 5. Lower story of the *Gussoni-Grimani* palace, which is at the mean see level. The figure shows the areas where the bricks were removed from (labels: A, B, C, D).

cracks or dislodging particles of material. No grinding was performed; no water was used during sawing. Actually, only few specimens were damaged during removal and subsequent operations, which were eliminated. The specimens that were discarded because of damage induced during specimen preparation (Fig. 10) were A2_8, A2_13, B2_7, B2_8, C2_4, D2_10, and D2_11). The damage which they were discarded for consisted of inclusion of nodules (Fig. 10a), cracking (Fig. 10b) or inclusion of anomalous bodies (Fig. 10c). Hence, 70 specimens were considered in the experimental campaign.

The diameter of every specimen was 30 mm. The length of each specimen was the height of the brick that it had been removed from minus the reduction due to the above-mentioned sawing process. Since the bricks were handmade, the heights of the bricks were not equal to each other; therefore, the specimens had different length from each other (Table 1).

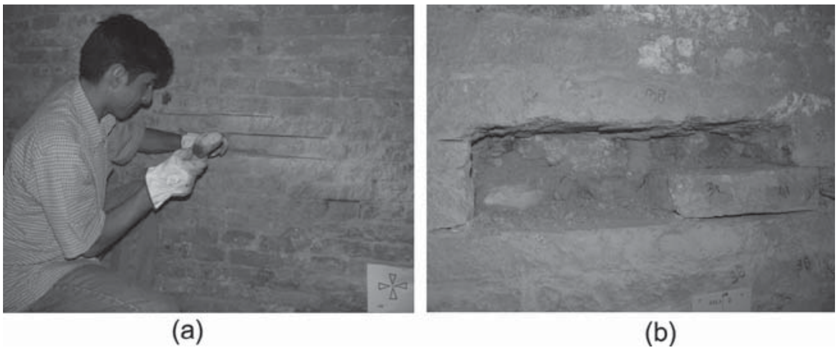


Fig. 6. Removal of the bricks from the walls. (a) Remove-brick-operation. (b) Hole in the wall after the removal of a brick.

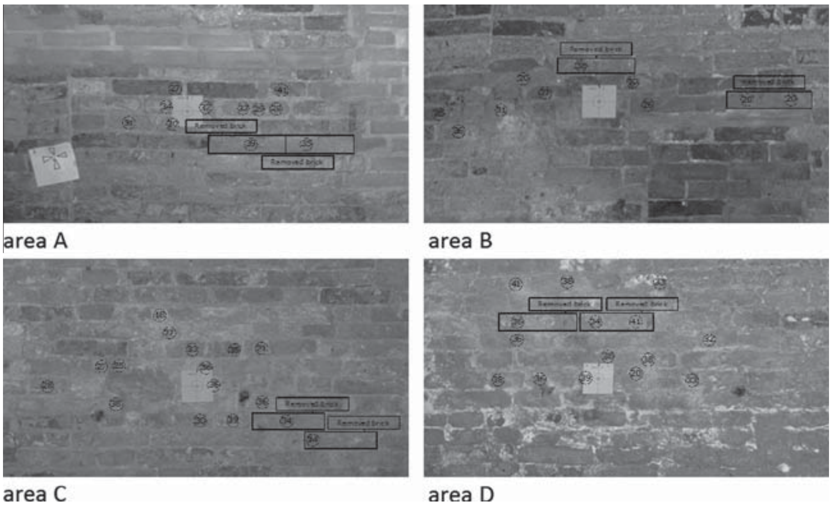


Fig. 7. Sclerometric analysis performed before removing the bricks (i.e., before accomplishing the operation shown in Fig. 6). The photos show the rebound index of each test. These indexes showed the bricks whose removal would have provided non-disturbed specimens.

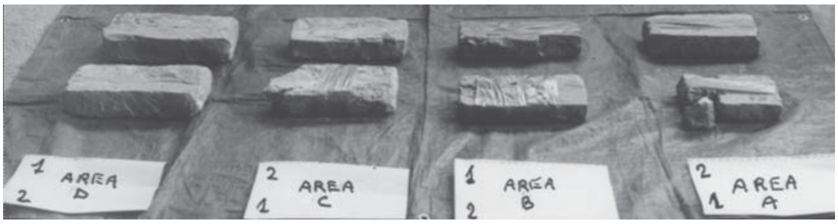


Fig. 8. Bricks removed from the walls and accepted for the testing. The specimens were extracted from these bricks only.

4.2. Test methodology

The first step of the experimentation, although had provided unsatisfactory compression test results, however, had found an important result about moisture and salt crystallization – namely, that masonry was in one of the following 4 conditions (from the less to the most severe).

(1) The masonry never in contact with the water of the lagoon and never in contact with the meteoric water was dry and exhibited low salt concentration (at the upper levels of the inner walls).
(2) The masonry never in contact with the water of the lagoon but in contact with the meteoric water was water-saturated and exhibited low salt concentration (at the upper levels of the outer walls).
(3) The masonry in contact with the water of the lagoon only during the high water due to the tides was dry and exhibited high salt concentration (at the level of the inner walls that was just above the mean sea level).

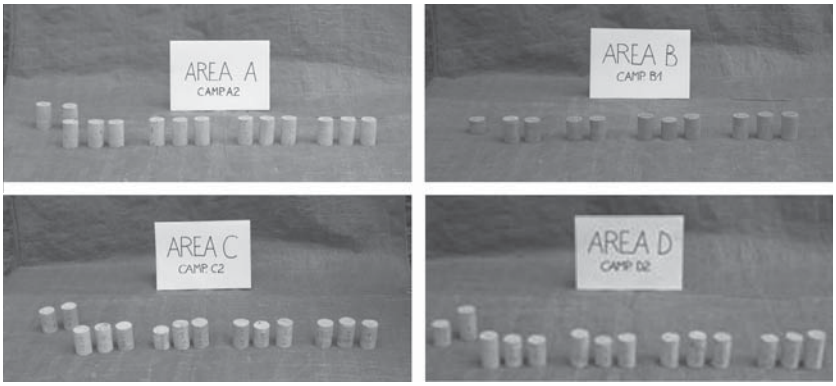


Fig. 9. Cylindrical specimens extracted from the bricks of Fig. 8.

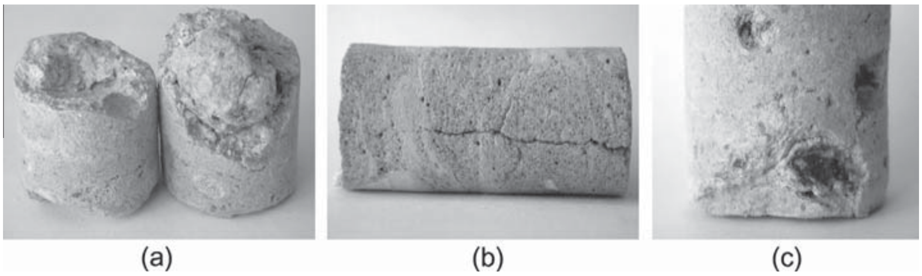


Fig. 10. Specimens damaged during the extraction from the bricks and the subsequent operations. These specimens were eliminated. The figure shows the three types of damage that were found in the specimens. (a) Damage due to nodules. (b) Damage due to cracking. (c) Damage due to inclusion of anomalous bodies.

Table 1
Specimens that were tested. Length of the cylindrical specimens, in mm. Labels of the specimens. The letter denotes the area of the building where the brick was removed from (Fig. 5); the first number denotes the brick; the second number denotes the specimens of that brick.

Label	Length	Label	Length	Label	Length	Label	Length
A1_1	46.1	B1_1	46.0	C1_1	55.5	D1_1	62.7
A1_2	46.3	B1_2	41.5	C1_2	55.2	D1_2	56.0
A1_3	43.7	B1_3	40.2	C1_3	55.7	D1_3	61.7
A1_4	44.7	B1_4	41.2	C1_4	55.2	D1_4	60.0
A1_5	50.5	B1_5	45.5	C1_5	54.2	D1_5	61.3
A1_6	51.3	B1_6	36.3	C1_6	54.4	D1_6	59.8
A2_1	50.0	B1_7	43.0	C2_1	46.7	D2_1	56.3
A2_2	49.3	B1_8	43.8	C2_2	46.6	D2_2	47.1
A2_3	48.3	B1_9	46.6	C2_3	45.8	D2_3	46.6
A2_4	51.2	B1_10	48.0	C2_5	46.9	D2_4	58.0
A2_5	50.4	B2_1	44.3	C2_6	47.8	D2_5	45.4
A2_6	51.9	B2_2	48.0	C2_7	46.7	D2_6	51.6
A2_7	51.7	B2_3	48.2	C2_8	40.6	D2_7	52.3
A2_9	51.4	B2_4	51.0	C2_9	46.3	D2_8	55.6
A2_10	51.5	B2_5	46.4	C2_10	45.8	D2_9	53.5
A2_11	49.6	B2_6	52.5	C2_11	49.6	D2_12	52.2
A2_12	49.7	/	/	C2_12	46.6	D2_13	57.0
A2_14	49.6	/	/	C2_13	43.4	D2_14	62.2

(4) The masonry in permanent contact with the water of the lagoon was nearly saturated with water and exhibited high salt concentration (at the lowest level of every wall).

In the second step of the research, the specimens extracted from the bricks were subjected to treatments directed towards modifying the moisture content and the salt concentration. The purpose of the treatments was to reproduce the above-described four conditions exhibited by the bricks.

The moisture content and the salt concentration that had been found in the first step of the experimental campaign were obtained by performing four types of treatments. In so doing, the moisture content and salt concentration of each specimen, not only reproduced the possible conditions of the bricks in the walls of the Venetian buildings, but also were known and uniform within each brick.

The treatments were accomplished by fulfilling specific procedures [47], which ensured the obtainment of the four identified conditions.

(1) The condition of the masonry in contact with neither the water of the lagoon nor the meteoric water (dry without salts) was reproduced by subjecting 11 specimens to a washing process. Each specimen was kept in a basin full of distilled water, for 28 days. The water was changed every day, so that the specimen was always immersed into non-saturated water. In so doing, the salts were completely removed from the specimen (brick-washing process). Then, each specimen was put into a convection oven, for eight hours. In so doing, the moisture was completely removed (brick-heating process).

(2) The condition of the masonry never in contact with the water of the lagoon but in contact with the meteoric water (water-saturated without salts) was reproduced by subjecting 24 specimens to the same brick-washing process used to reproduce the first condition. Conversely, no brick-heating process was performed, before or after the washing process, in this case.

(3) The condition of the masonry in contact with the water of the lagoon only during the high water due to the tides (dry with salts) was reproduced by subjecting 24 specimens to the same brick-heating process used to reproduce the first condition. Conversely, no brick-washing process was performed in this case.

(4) The condition of the masonry in permanent contact with the water of the lagoon (water-saturated with salts) was reproduced by subjecting 11 specimens to a process that saturated each specimen with water, without modifying the salt concentration of the specimen. To this end, each specimen was placed onto a grid located into a ceramic basin. The grid left a gap between the specimen and the bottom of the basin. Distilled water continuously dripped onto the brick and then drained away through the gap below the brick. In so doing, the specimen was not made sodden, which would have altered the salt concentration into the specimen; i.e., the grid allowed the water to drain, preventing the salt contained into the specimen from joining the solution. This treatment was carried out for 28 days.

Before and after a treatment, the weight of each specimen was measured. In the case of the water-saturated specimens, the comparison between the weights before and after the treatment provided the percentage of the total porosity of the specimen.

Ultimately, the test methodology followed in the second step of the experimental campaign provided specimens whose moisture content and salt concentration were known, and reproduced the four conditions that had been found in the first step of the experimental campaign for the walls of *Gussoni-Grimani* palace. It is to note that the conditions found for *Gussoni-Grimani* palace are the typical conditions of the Venetian buildings.

4.3. Test results

Each specimen was subjected to uniaxial compression test (Fig. 11), to determine the ultimate stress of the brick in the various conditions. Hence, the tests determined the compression strength of each tests, defined as the ratio between the axial force applied just before crushing and the area of the cross-section of the specimen at the start of the test.

Since the specimens were small and brittle, they exhibited loading-rate sensitivity, and thus needed to be detected with high sensitivity. The tests were designed so as to fulfill this requirement. The testing machine was of a type having sufficient capacity (Fig. 11). Moreover, the testing machine was capable of providing adequate low rates of loading. Thus, very small increments of load could to be applied to each specimens and the conditions of the specimen could be checked at each loading step. In so doing, the initiation of the first crack could be identified. The accuracy of the testing machine was in accordance with very strict requirements [48,49].

In order to take into account the ratio between the height h and diameter d of the cylindrical specimens (h/d is the slenderness), the values of the compression strength measured in the tests were multiplied by a corrective coefficient α, according to [48]:

$$\alpha = \frac{2}{1.5 + \frac{d}{h}} \tag{8}$$

It is to note that if α would have been estimated by fulfilling [49], almost the same values would have been obtained.

The results of the tests are represented in four curves, which show the values of the compression strength obtained for all the specimens, grouped on the basis of the treatment which they were subjected to (Fig. 12). Each curve is composed of a set of discrete points; the abscissa of each point is used to differentiate the specimens from each other, sorting the compression strength in ascending order, and the ordinate of each point represents the compression strength measured for each specimen. Hence, Fig. 12 shows four curves, one curve for each treatment – namely, dry without salts, water-saturated without salts, dry with salts, water-saturated with salts.

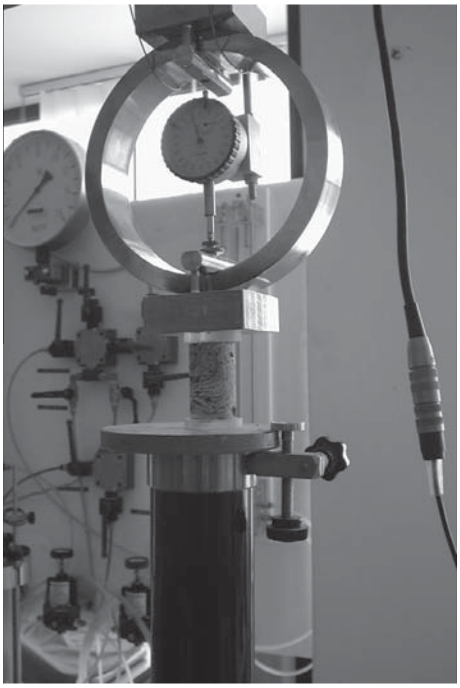


Fig. 11. Compression tests carried out on the cylindrical specimens extracted from the bricks.

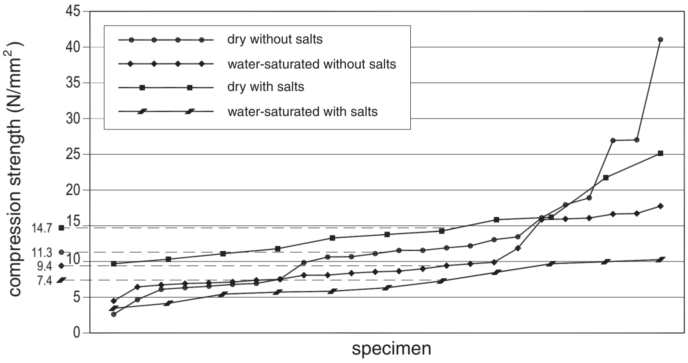


Fig. 12. Compression strength measured for all the specimens. Each of the four curves considers specimens that were subjected to the same treatment, which is indicated above each graph. The four curves are plotted in a single graph, so as to provide a direct comparison between the values obtained from all the tests. The figure also shows the average compression strength of each curve (ultimate stress values on the left of the ordinate).

5. Discussion

In order to properly interpret the experimental results, other graph representations are provided, which better represent the outputs. In particular, research was directed towards gaining a fundamental understanding of the effects of moisture content and salt concentration on compression strength of bricks. Consequently, the figures plot the experimental correlations that may provide qualitative and quantitative estimations of the reduction in compression strength due to these factors. In particular, this section provides information for structural designers and repair specialists for proper structural condition assessment and subsequent structural intervention design, necessary to avoid failure [50–53].

Fig. 13 shows the results of the statistical analysis of the experimental strength values. Two different graphical representations are provided (Fig. 13a and b). In each representation, the values of the experimental strength are divided into mutually exclusive groups, based on the treatments that the specimens were subjected to; i.e., four groupings of results for each graphical representation. Hence, eight graphs are shown in total in Fig. 13. The abscissa of each of the eight graphs represents the ultimate stress of the specimens (N/mm^2). The ordinate of each of the eight graphs represents a histogram that provides the statistical distribution of the ultimate stress. More specifically, the ordinate of Fig. 13a is the number of values within the

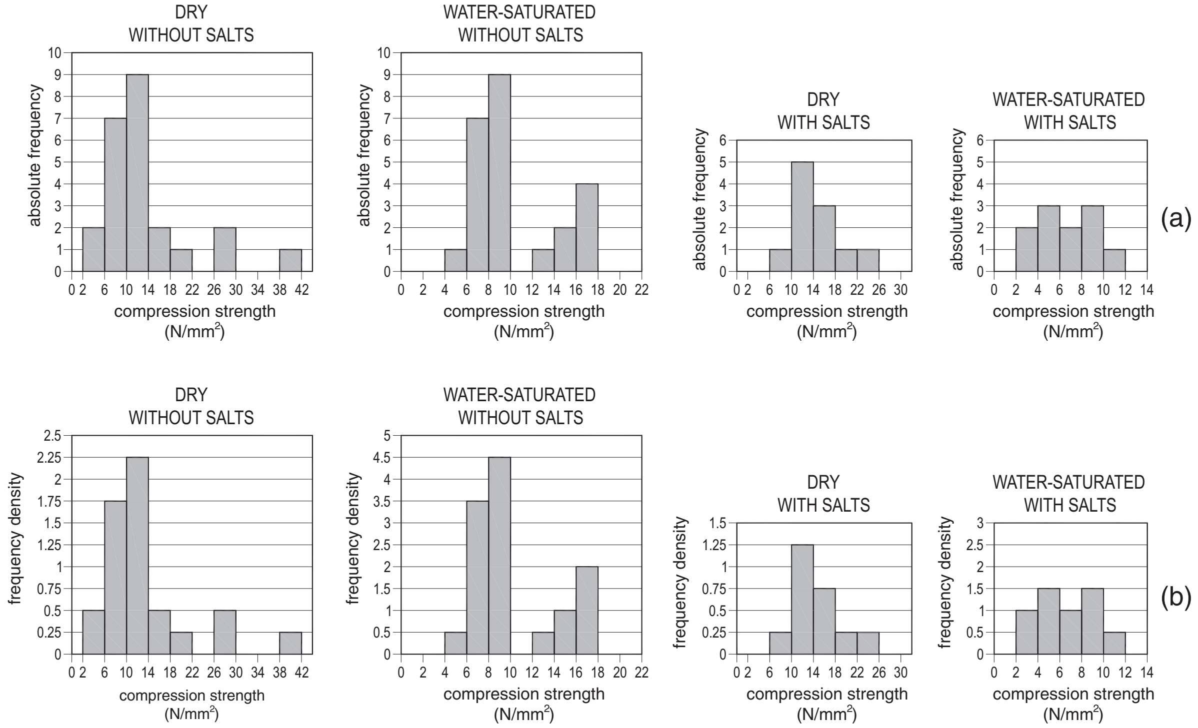


Fig. 13. Histograms of the ultimate compression stress (compression strength) measured for the specimens subjected to the same treatment. (a) Absolute frequency, defined as the number of values within the interval on the abscissa. (b) Frequency density, defined as the number of values within the interval on the abscissa, divided by the number of specimens considered by the graph.

interval on the abscissa (absolute frequency); the ordinate of Fig. 13b is the number of values within the interval on the abscissa divided by the number of specimens considered by the graph (frequency density).

Fig. 14 divides the experimental strength values into four groups, according to the treatment that each specimen had been subjected to. Thus, each group considers specimens with the same treatment. For each of these groups, Fig. 14 presents a graph whose abscissa gathers the specimens extracted from the same brick together, and whose ordinate represents the compression strength of each specimen. Consequently, each graph shows the variance of the compression strength due to the intrinsic dishomogeneity within a brick as well as within all the bricks of the building. Hence, Fig. 14 quantifies the incidence of the fact that the bricks were handmade.

Fig. 15 considers four bricks, removed from different areas of the building and positions of the walls. The figure is composed of four graphs – namely, one graph per brick. On the abscissa, each graph plots all the specimens that had been extracted from the same brick; on the ordinate, each graph plots the compression strength of these specimens. Hence, each graph considers specimens extracted from the same brick and subjected to both the same treatment and different treatments from each other. Thus, each graph allows comparison to be made between specimens whose behavior does not depend on the brick that they were extracted from. Consequently, this representation provides an unbiased estimation of the relationships between the compression strength of the bricks and the treatment. This means that Fig. 15 shows the dependence of the compression strength on moisture content and salt concentration without showing any unfair tendency.

Fig. 16 divides the specimens into three mutually exclusive groups on the basis of the treatment they had been subjected to (the dry-with-salt specimens were not considered in this figure). For each group, Fig. 16 shows a graph whose ordinate represents the compression strength of the specimens of that group and whose abscissa represents their porosity (the volume of voids over the total volume of the specimen). Hence, each of the three graphs shows the relationship between the porosity and the compression strength of the brick. This figure points out the influence of the void fraction upon the compression strength of the bricks, including the fact that the bricks were handmade, which influences the porosity. This figure ignores the dry-with-salt specimens because these specimens were not water-saturated and the porosity was obtained from the difference between the water-saturated weight and the dry weight of the specimen.

5.1. Conclusions that can be drawn on the effects of moisture content and salt concentration upon the compression strength of bricks

The results obtained from the experimental campaign show that the average compression strength of the dry specimens with salts is equal to 14.7 N/mm^2; it is the maximum of the four average values. The average compression strength of the dry

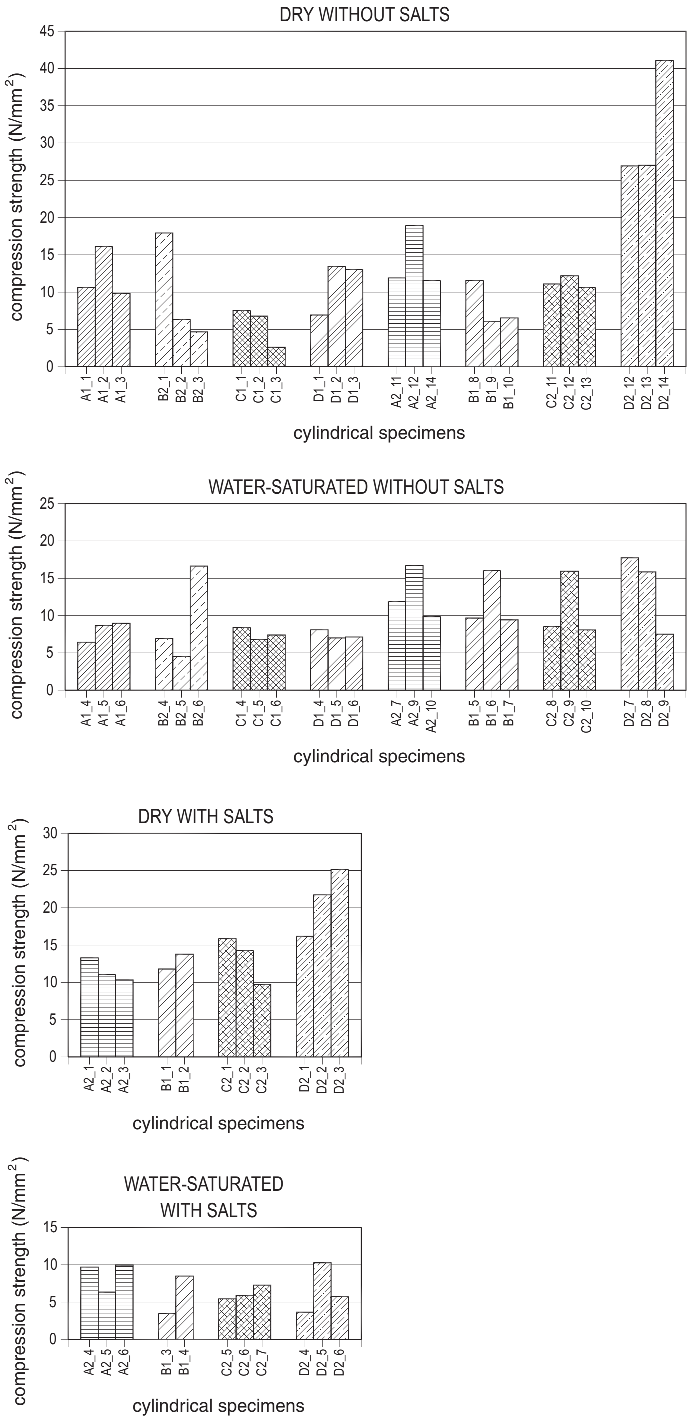


Fig. 14. Compression strength of the specimens that were subjected to the same treatment. The abscissa gathers the specimens extracted from the same brick together, in order to shows the dependence of the compression strength on the composition of the bricks only.

specimens without salts, which ranks second, is 11.3 N/mm^2. The average compression strength of the water-saturated specimens without salts, which ranks third, is 9.4 N/mm^2. The average compression strength of the water-saturated specimens with salts, which is the minimum of the four average values, is 7.4 N/mm^2 (Figs. 12 and 13).

The experimental data demonstrate that moisture substantially affects the compression strength of bricks, and that the way moisture affects the strength is univocal – namely, moisture causes a decrease in the compression strength for bricks,

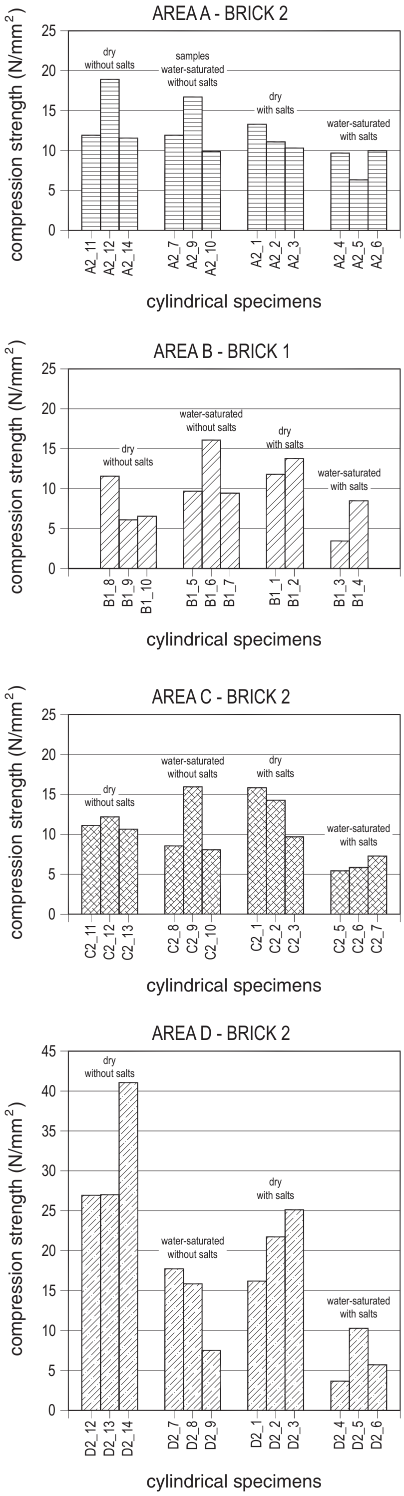


Fig. 15. Compression strength of the specimens extracted from four bricks removed from four different areas of the building (i.e., the selected areas shown in Fig. 5). The abscissa gathers the specimens that were subjected to the same treatment together.

whatever the salt concentration. In fact, the average compression strength of the water-saturated specimens with or without salts is lower than that of the dry specimens with or without salts. More specifically, the average compression strength of the water-saturated specimens ranges from 7.4 to 9.4 N/mm^2, while the average compression strength of the dry specimens ranges from 11.3 to 14.7 N/mm^2, depending on salt concentration.

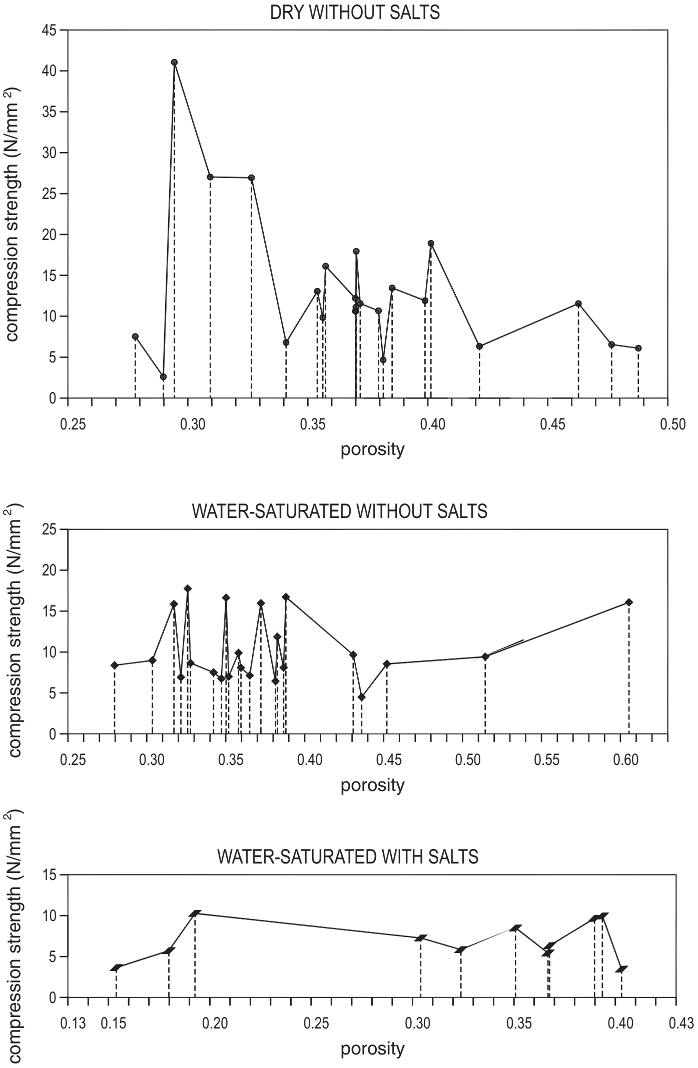


Fig. 16. Abscissa: Porosity (void fraction), defined as the volume of voids over the total volume of the specimen. Ordinate: compression strength of the specimens subjected to the same treatment. Dry-with-salt specimens are not included in this figure, since their porosity could not be measured. In fact, porosity was obtained from the difference between the water-saturated weight and the dry weight of the specimen, and these specimens were not water-saturated.

The above result holds true for specimens that, without water and salts, exhibited similar compression strength. These comparisons prove that the differences in compression strength were not due to differences in composition and manufacturing process of the bricks, but on moisture.

The experimental data also demonstrate that salts substantially affect compression strength of bricks, but the way that salts affect strength is not univocal. In fact, the average compression strength of the water-saturated specimens with salts is the lowest, while the average compression strength of the dry specimens with salts is the highest. More specifically, the average compression strength of the specimens with salts ranges from 7.4 to 14.7 N/mm^2, while the average compression strength of the specimens without salt ranges from 9.4 to 11.3 N/mm^2, depending on moisture.

Ultimately, the experimental results indicate that moisture significantly reduces the compression strength of a brick; the greater the moisture content the lower the compression strength, all other condition being equal, in particular the salt concentration inside the brick. Moreover, the experimental results indicate that salts together with moisture significantly reduce the brick compression strength, while salts without moisture increase the brick compression strength.

However, this last finding is not a standalone result, but it has to be considered in the context. In a brick with salts, in fact, crystallization can take place within the brick's pores and can eventually cause severe mechanical damage to masonry as a result of subflorescence and efflorescence. On the contrary, the tested bricks suffered from subflorescence and efflorescence, but not from the damage induced by these phenomena. If the bricks also had suffered from the mechanical damage induced by subflorescence and efflorescence, compression strength would have resulted to be much lower than the values measured in the tests. Thus, the salts should be removed from the bricks, even when they may increase the compression strength.

The experimental results exhibited large dispersion independently of the moisture content and salt concentration of the bricks (Fig. 14). Dispersion was mainly due to the fact that the composition and manufacturing of the Venetian bricks, which were handmade, caused dishomogeneity of several types. Nonetheless, also the age-related effects on the mechanical behavior of the bricks resulted to be different even within the same bricks. Thus, the results show that the level of dishomogeneity of handmade age-old bricks is high.

This research found that there is another source of dispersion for brick compression strength in addition to manufacturing process – namely, moisture and salt crystallization. Not only do moisture content and salt concentration reduce significantly the compression strength of a brick, all other parameters being equal (Fig. 15), but also they increase the dispersion of the compression test results. Thus, the greater the moisture content and salt concentration inside a bricks, the lower the level of knowledge that can be reached on the mechanical behavior of the brickwork and of the masonry building.

Ultimately, the degree of confidence that can be reached on the mechanical behavior of masonry made of handmade age-old bricks with moisture and salts is rather low, unless a huge number of tests are accomplished. However, a huge number of in-situ tests would be in contrast to the requirement that the tests in historical buildings have to be non-destructive.

Fig. 16 shows that the compression strength does not depend on the porosity of the brick. This result does not depend on the salt concentration but it holds true for all the conditions of the specimens. Hence, Fig. 16 suggests that, on one hand, the lower the porosity of the brick the greater the force transmitted by the unit area of the brick, since there is more material within the unit area. On the other hand, however, the greater the porosity of the brick the better the way the clay is baked in the kiln. These two effects compensate one another; in the end, the compression strength is not affected by the porosity.

The above result found at the scale of the specimen something already known at the scale of the brick. In fact, for the same reason, the compression strength of a perforated brick with less than 25–30% perforations by volume is greater than that of a solid brick.

6. Closing remarks

Activity was directed at analyzing the mechanical effects of moisture and salt crystallization on bricks, carrying out research to help reduce the incidences of failure due to these factors, and extending the operating horizons of the techniques that remove moisture and salts.

The results of compression tests performed on specimens extracted from bricks of a Venetian building demonstrate that moisture causes a dramatically decrease in the compression strength of a brick, which is even more pronounced if the brick is also subject to a salt solution.

Moisture and salts were induced artificially. Four combinations of moisture content and salt concentration were constructed in laboratory for the specimens, which reproduced all the environmental conditions found in this building, as well as in almost all the Venetian buildings. Thus, the results of this research can be extended to any masonry building subjected to moisture and salt crystallization.

Ultimately, this research has come to the conclusion that, in the presence of trapped moisture, the compression strength of a brick is substantially lower than that of the dry brick, and that this reduction strongly depends on the salt content. Moreover, the research has come to the conclusion that, in the presence of salts, the compression strength of a brick may be either lower or higher than that of the brick without salts, depending on the moisture content.

The research has also demonstrated that moisture content and salt concentration in brick masonry buildings exhibit high variance. In fact, these factors depend on the relationships of each portion of wall with both the brackish water and the meteoric water (i.e., walls that are at the lower or upper stories, external or internal). The great influence of the moisture content and salt concentration on the compression strength of a brick implies that the compression strength of brickworks subjected to brackish water, tides, or meteoric water exhibit high variance as well.

Therefore, in order to reach an adequate level of knowledge (i.e., degree of confidence) of the compression strength, numerous tests have to be accomplished for those brickworks. However, while in situ measurements of both moisture and salts can be accomplished in a non-destructive fashion, in situ and laboratory measurements of the brick compression strength can be accomplished only in a destructive fashion.

Only non-destructive tests are allowed to be performed in a historical building. Thus, a historical building allows trapped moisture and salts to be measured in a great number of points, while it allows the compression strength to be measured in only a few points. In order to predict the ultimate stress of historical masonry, hence, structural analysis has to consider the relationships provided in this paper between the brick compression strength and the combination of moisture content and salt concentration.

If safety assessment of a building subjected to brackish water, meteoric water and/or tides demonstrates that masonry compression strength is deficient, the results of this research suggest increasing the structural capacity by modifying the moisture content and salt concentration in the bricks.

However, the research has also obtained an unexpected result – namely, that salts may increase the compression strength of the bricks. Accordingly, while the treatments that unsaturate the bricks seem to increase the compression strength in any sort of conditions, the treatments that remove the salts seem to increase the compression strength only in some conditions.

This piece of novel information could not be related to existing knowledge on the topic, since the literature did not give an unambiguous picture on the techniques that remove moisture and salts from masonry.

To provide further insight into this issue, the results of this research needed to be interpreted in a different way before assessing their implications and before drawing conclusions. This research has found that the compression strength of a brick which is dry without salts is greater than that of the same brick with both moisture and salts, whatever the moisture content and salt concentration; nevertheless, the condition in which a brick reaches the highest compression strength is when it is dry with salts.

However, salts crystallize (because the crystalline form is energetically favored) and salt crystallization inside the brick leads to the formation of subflorescence and efflorescence, which can eventually cause mechanical damage to the bricks. Damage includes cracks inside the brick, localized crumbling, defoliation, spalling of the brick faces, and eventually dislodging of the individual masonry units. Furthermore, salts cause the compression strength to exhibit high variance (high statistical dispersion of the values).

Ultimately, on one hand, the average compression strength of the dry-with-salt bricks is greater than that of the same brick in any other conditions. On the other hand, however, the strength values obtained for the dry-with-salt bricks are not permanent, because subflorescence and/or efflorescence may take hold or have already taken hold. Hence, safety assessment has to consider the decrease in compression strength of the bricks due to damage eventually induced by those factors.

Moreover, the greater the salt concentration the greater the variance of the compression strength, and consequently the lower the characteristic value with respect to the average value.

In brick masonry structures, thus, not only does moisture removal provide a significant increase of compression strength, but also salt removal provides safety assessment with a greater value of the design compression strength.

Acknowledgments

The tests were sponsored by CO.RI.LA (*Consortium for coordination of research activities concerning the Venice lagoon system*), within the program *"Scientific Research and Safeguarding of Venice"*. The authors wish to acknowledge Prof. Mario Piana and Prof. Paolo Faccio, of Università IUAV di Venezia (Italy), who organized and coordinated the research *"Protection of Venice from the lagoon water"*, and supported the experiments presented in Section 4.

References

[1] Gieskesa JM, Elwany H, Rasmussen L, Han S, Rathburn A, Deheyne D. Salinity variations in the Venice Lagoon, Italy: results from the SIOSED Project, May 2005–February 2007. Mar Chem 2013;154(20):77–86.
[2] Umgiesser G, Zampato L. Hydrodynamic and salinity modeling of the Venice channel network with coupled 1-D–2-D mathematical models. Ecol Model 2001;138(1–3):75–85.
[3] Binda L, Saisi A, Tiraboschi C. Investigation procedures for the diagnosis of historic masonries. Constr Build Mater 2000;14(4):199–233.
[4] Gummerson RJ, Hall C, Hoff WD. Water movement in porous building materials—II. Hydraulic suction and sorptivity of brick and other masonry materials. Build Environ 1980;15(2):101–8.
[5] Andrés A, Díaz MC, Coz A, Abellán MJ, Viguri JR. Physico-chemical characterisation of bricks all through the manufacture process in relation to efflorescence salts. J Eur Ceram Soc 2009;29(10):1869–77.
[6] Antonelli F, Cancelliere S, Lazzarini L. Minero-petrographic characterisation of historic bricks in the Arsenale, Venice. J Cultural Heritage 2002;3(1):59–64.
[7] Calliari I, Canal E, Cavazzoni S, Lazzarini L. Roman bricks from the Lagoon of Venice: a chemical characterization with methods of multivariate analysis. J Cultural Heritage 2001;2(1):23–9.
[8] Díaz Gonçalves T, Delgado Rodrigues J, Marinho Abreu M. Evaluating the salt content of salt-contaminated samples on the basis of their hygroscopic behaviour: Part II: Experiments with nine common soluble salts. J Cultural Heritage 2006;7(3):193–200.
[9] Lubelli B, van Hees RPJ, Groot CJWP. The role of sea salts in the occurrence of different damage mechanisms and decay patterns on brick masonry. Constr Build Mater 2004;18(2):119–24.
[10] Raimondo M, Dondi M, Mazzanti F, Stefanizzi P, Bondi P. Equilibrium moisture content of clay bricks: the influence of the porous structure. Build Environ 2007;42(2):926–32.
[11] Ludovico-Marques M, Chastre C. Effect of salt crystallization ageing on the compressive behavior of sandstone blocks in historical buildings. Eng Fail Anal 2012;26(December):247–57.
[12] Carcangiu G, Casti M, Desogus G, Meloni P, Ricciu R. Microclimatic monitoring of a semi-confined archaeological site affected by salt crystallisation. J Cultural Heritage; 2014. [in Press], Corrected Proof, Available online 4 March 2014.
[13] Karoglou M, Moropoulou A, Giakopumaki A, Krokida MK. Capillary rise kinetics of some building materials. J Colloid Interface Sci 2005;284(1):260–4.
[14] Karoglou M, Moropoulou A, Krokida MK, Maroulis ZB. A powerful simulator for moisture transfer in buildings. Build Environ 2007;42(2):902–12.
[15] Sawdy A, Pric C. Salt damage at Cleeve Abbey, England. Part II: seasonal variability of salt distribution and implications for sampling strategies. J Cultural Heritage 2005;6(3):269–75.
[16] Zanchet Piaia JC, Cheriaf M, Cavalcante Rocha J, Luperont Mustelier N. Measurements of water penetration and leakage in masonry wall: experimental results and numerical simulation. Build Environ 2013;61:18–26.
[17] Pel L, Huinink H, Kopinga. Salt transport and crystallization in porous building materials. Magn Reson Imaging 2003;21(3–4):317–20.
[18] De Freitas VP, Abrantes V, Crausse P. Moisture migration in building walls—analysis of the interface phenomena. Build Environ 1996;31(2):99–108.
[19] Hall C, Hoff WD, Nixon MR. Water movement in porous building materials—VI. Evaporation and drying in brick and block materials. Build Environ 1984;19(1):13–20.
[20] Koniorczyk M, Gawin D. Modelling of salt crystallization in building materials with microstructure – poromechanical approach. Constr Build Mater 2012;36:860–73.
[21] Kääriäinen H, Rudolph M, Schaurich D, Tulla K, Wiggenhauser H. Moisture measurements in building materials with microwaves. NDT and E Int 2001;34(6):389–94.
[22] Litavcova E, Korjenic A, Korjenic S, Pavlus M, Sarhadov I, Seman J, et al. Diffusion of moisture into building materials: a model for moisture transport. Energy Build 2014;68(Part A):558–61.

[23] Lubelli B, van Hees RPJ, Brocken HJP. Experimental research on hygroscopic behaviour of porous specimens contaminated with salts. Constr Build Mater 2004;18(5):339–48.

[24] Brocken H, Nijland TG. White efflorescence on brick masonry and concrete masonry blocks, with special emphasis on sulfate efflorescence on concrete blocks. Constr Build Mater 2004;18(5):315–23.

[25] Castellazzi G, Colla C, de Miranda S, Formica G, Gabrielli E, Molari L, et al. A coupled multiphase model for hygrothermal analysis of masonry structures and prediction of stress induced by salt crystallization. Constr Build Mater 2013;41:717–31.

[26] Gentilini C, Franzoni E, Bandini S, Nobile L. Effect of salt crystallisation on the shear behaviour of masonry walls: an experimental study. Constr Build Mater 2012;37:181–9.

[27] van Hees RPJ, Brocken HJP. Damage development to treated brick masonry in a long-term salt crystallisation test. Constr Build Mater 2004;18(5):331–8.

[28] Janssen H, Derluyn H, Carmeliet J. Moisture transfer through mortar joints: a sharp-front analysis. Cem Concr Res 2012;42(8):1105–12.

[29] Ural A, Oruç Ş, Doğangün A, Tuluk Öİ. Turkish historical arch bridges and their deteriorations and failures. Eng Fail Anal 2008;15(1–2):43–53.

[30] Fassina V, Favaro M, Naccari A, Pigo M. Evaluation of compatibility and durability of a hydraulic lime-based plaster applied on brick wall masonry of historical buildings affected by rising damp phenomena. J Cultural Heritage 2002;3(1):45–51.

[31] Franzoni E, Bandini S, Graziani G. Rising moisture, salts and electrokinetic effects in ancient masonries: from laboratory testing to on-site monitoring. J Cultural Heritage 2014;15(2):112–20.

[32] Maierhof Ch, Wöstmann J. Investigation of dielectric properties of brick materials as a function of moisture and salt content using a microwave impulse technique at very high frequencies. NDT and E Int 1998;31(4):259–63.

[33] Nardini I, Zendri E, Biscontin G, Brunetin A. Analytical methods for the characterization of surface finishing in bricks. Anal Chim Acta 2006;577(2):276–80.

[34] EN 1996. Eurocode 6. Design of masonry structures; 1996.

[35] Hendry AW. Introduction to Load Bearing Brickwork Design, August. Ellis Horwood Ltd. Publisher; 1981. p. 184.

[36] Hendry AW. Structural masonry. London: Macmillan Press Ltd.; 1990.

[37] Hendry AW. Engineered design of masonry buildings: fifty years development in Europe. Progr Struct Eng Mater 2002;4(3):291–300.

[38] Hendry AW, Sinha BP, Davies SR. Design of masonry structures. London: E & FN Spon; 2004.

[39] Chen MC, Wang K, Xie L. Deterioration mechanism of cementitious materials under acid rain attack. Eng Fail Anal 2013;27:272–85.

[40] Bigoni D, Bosi F, Dal Corso F, Misseroni D. Instability of a penetrating blade. J Mech Phys Solids 2014;64:411–25.

[41] Biolzi L. Evaluation of compressive strength of masonry walls by limit analysis. J Struct Eng (ASCE) 1988;114(10):2179–89.

[42] Gagg CR. Cement and concrete as an engineering material: an historic appraisal and case study analysis. Eng Fail Anal 2014;40:114–40.

[43] Foraboschi P. Church of San Giuliano di Puglia: Seismic repair and upgrading. Eng Fail Anal 2013;33:281–314.

[44] Labuz JF, Biolzi L. Characteristic strength of quasi-brittle materials. Int J Solids Struct 1998;35(31–32):4191–203.

[45] Stupkiewicz S, Piccolroaz A, Bigoni D. Elastoplastic coupling to model cold ceramic powder compaction. J Eur Ceram Soc 2014;34(11):2839–48.

[46] Faccio P, Foraboschi P, Vanin A. Art of building and mechanical behavior of masonry panels. In: Proceedings of the sixth international masonry conference, 4–6 November, London; 2002. p. 132–9.

[47] BS 1881-122: Testing concrete method for determination of water absorption; 2011.

[48] BS 1881 P120. Method for determination of the compressive strength of concrete cores; 1983.

[49] ASTM Committee. Standard test method for obtaining and testing drilled cores and sawed beams of concrete; 2013.

[50] Barbieri G, Biolzi L, Bocciarelli M, Fregonese L, Frigeri A. Assessing the seismic vulnerability of a historical building. Eng Struct 2013;57:523–35.

[51] Foraboschi P. Coupling effect between masonry spandrels and piers. Mater Struct 2009;42(3):279–300.

[52] Vanin A, Foraboschi P. In-plane behavior of perforated brick masonry walls. Mater Struct 2012;45(7):1019–34.

[53] D'Ambrisi A, Feo L, Focacci F. Masonry arches strengthened with composite unbonded tendons. Compos Struct 2013;98(April):323–9.