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Effect of salt crystallisation on the shear behaviour of masonry walls: An experimental study

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HIGHLIGHTS

- ▶ Experimental study conducted on artificially salt weathered masonry specimens.
- ▶ Investigation on shear behaviour of the brick/mortar interface.
- ▶ Main mechanical and material microstructural parameters are correlated.
- ▶ Presence of salt affects the structural behaviour of masonry.

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ABSTRACT

Salt weathering is one of the most common deterioration mechanisms in porous materials and may lead to severe damage in buildings and artworks. In last decades, a lot of research has been devoted to explain the mechanisms of crystal growth and crystallisation pressure inside pores and their relation with crack propagation in materials such as natural stone, brick, mortar and concrete. However, the effect of salts on the structural behaviour of masonry has not been fully elucidated.

This paper presents a preliminary experimental study conducted on masonry specimens made of fired-clay bricks and cement mortar joints in order to assess the structural damage induced by salts. To this aim, the specimens were subjected to purposely-designed accelerated weathering procedures of different duration in sodium chloride and sodium sulphate solutions (the most common salts in brick masonries). Then, the shear behaviour of the artificially damaged masonry specimens was investigated by means of an *ad hoc* experimental test. As well known, the shear behaviour of masonry buildings plays a crucial role for structures located in areas prone to seismic hazard.

The main mechanical parameters that result from the analysis of the pre-peak behaviour of the specimens, such as initial stiffness and peak load, have been correlated to the main material microstructural parameters (total porosity and pore size distribution) and to salt amount. It has been observed that the presence of salt affects the structural behaviour of masonry depending on the type of salt and on the duration of the weathering cycles.

1. Introduction and research aims

Architectural heritage undergoes several decay processes due to the exposure to aggressive environmental conditions that threaten its durability and preservation [1]. Moisture, whose presence may be due to rain, condensation or capillary rise [2], plays a key role in the degradation of porous materials [3,4], being directly or indirectly responsible for several decay processes [5], such as freeze–thaw cycles, soluble salts crystallisation cycles, biological growth, chemical attack by acid rain and wind erosion.

Salt crystallisation cycles deserved particular attention [6,7], since they cause pressure inside porous materials (sub-florescence) and may induce the rupture of the pores walls [8], leading to disruptive effects [9], such as pulverisation, crumbling, blistering and flaking [7,10]. Much research effort has been devoted to investigate the damage mechanisms due to salt attack in materials such as natural stone, concrete and masonry [11]. Several aspects have been considered, such as the generation of stress due to salt crystal growth and the consequent mechanical disintegration of pores [12], the pressure related to confined crystallisation within stones [13], the crystallisation phenomenon in porous materials subjected to accelerated aging [14] and the migration and crystallisation of salts within porous and cracked materials [15]. Key contributions to the appraisal of the stress related to salts inside the materials' pores

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were given in [6,7,10], where the thermodynamic and kinetic equations governing the crystallisation in porous materials and the factors that influence stress development and cracking were analysed. Nevertheless, the conditions at which the salt crystallisation leads to crack propagation and failure of the material are still under study [7].

While the effects of moisture and salts on material degradation processes have been widely investigated, the effects of moisture and salts on the masonry structural performance still deserve further investigation. In fact, the need of an accurate description of mechanical behaviour of salt damaged masonry for developing possible intervention and/or restoration techniques has been recently pointed out [16].

In this paper, an experimental contribution to the knowledge of the shear behaviour of masonry affected by moisture and salts is given, with particular attention to the evaluation of structural damage induced by salts at the brick/mortar interface. In fact, the load bearing capacity of masonry structures strongly depends on the quality of the bonding between brick and mortar, and this takes additional importance for out of plane loading conditions, such in the case of earthquakes. The building stock in several countries is largely constituted by masonries, hence understanding their behaviour in case of earthquake is of great importance [17,18]. In particular, as masonries are often altered by moisture and salts, their actual state should be considered for a more accurate appraisal of their structural behaviour.

To this purpose, laboratory-scale masonry models made of fired-clay bricks and cement mortar joints were prepared. Then, their behaviour under shear loading, in terms of initial stiffness, peak loads and displacements, was assessed in dry conditions, in water-saturated conditions and after salt crystallisation cycles, respectively. As preliminary step, the study focussed on the initial part of the load–displacement curves, up to the peak load. Sodium sulphate and sodium chloride were selected for the tests, as the first one is widely recognised among the most weathering salts [19,20], while the second one represents the most common soluble salt in historical buildings [12,21–23]. The weathering procedure (salt crystallisation cycles) was purposely designed to produce salt amounts in the specimens comparable to those currently found in real masonries [24], rather than causing the fracture of the specimens. In fact, accelerated salt crystallisation procedures already exist in literature [14,25–27], but the determination of the resistance of porous specimens against sulphates and chlorides is determined only from a qualitative point of view by visual inspection and weight loss [28]. In this work, the experimental approach is aimed at evaluating quantitatively the structural damage for masonry walls induced by salt weathering. It is observed that salt weathering cycles affect the structural behaviour of the masonry samples depending on the nature of salts and on the number of the weathering cycles.

2. Material and experimental methods

2.1. Bricks and mortars

For laboratory-scale assemblies, commercial fired-clay masonry bricks $250 \times 120 \times 60\ \mathrm{mm}^3$ (IBL, Italy) were used. For mortar preparation, commercial siliceous sand (<2 mm) and CEM II 32.5 L were mixed in a Hobart mixer (EN 196-1), with aggregate/cement weight ratio 3/1. The water amount was adjusted in order to achieve suitable fresh-state mortar workability and the resulting water/cement ratio was 0.5. Cement and aggregate were mixed for 120 s at speed 1, then water was added and mortar was mixed for further 120 s at speed 1 and 30 s at speed 2.

2.2. Laboratory-scale experimental assemblies

The bricks were cut into $60 \times 75 \times 110\ \mathrm{mm}^3$ prisms for the manufacturing of the laboratory-scale experimental assemblies, whose structure and size are shown in Fig. 1. Each assembly was manufactured using three prisms obtained from the same brick, in order to avoid the microstructural heterogeneity occurring among different bricks. The mortar was applied to the previously wetted bricks with a thickness of 1 cm, i.e. in the range 5–15 mm recommended by Italian Standard (DM 14/01/2008) for masonries subjected to seismic actions. The assemblies were cured for 24 h at RH > 95% and T = 20 ± 5 °C and then for 1 month at room conditions. Three $40 \times 40 \times 160\ \mathrm{mm}^3$ specimens of mortar were also prepared for flexural and compressive strength testing (EN 196-1).

2.3. Conditioning procedure

After curing, a first series of samples (SAT samples) was saturated by immersion in clean water up to constant weight and a second series (REF samples) was kept dry without any further conditioning.

The other assemblies were exposed to artificial salt crystallisation cycles, according to the following procedure. Each cycle is constituted by two phases: (1) a wetting phase, in which the bottom of the assembly was kept for 4 days immersed in 2 cm of saline solution (Fig. 2), periodically replenished to assure a constant height; (2) a drying phase, in which the specimen was kept in a ventilated oven at 60 °C for 3 days. The disposition of the assembly in Fig. 2 was chosen to make the efflorescence and sub-efflorescence grow in correspondence of the lateral surfaces, where they actually occur in masonries; the same disposition is provided, *mutatis mutandis*, in the Recommendation RILEM TC 127-MS-A.1 [26], where the salt crystallisation cycle is prolonged up to the rupture of the masonry assemblies. For the cycles, clean water (W samples), 1 wt.% NaCl aqueous solution (CHL samples) and 1 wt.% Na_2SO_4 aqueous solution (SUL samples) were used, respectively.

Four and 10 cycles were performed and the relevant assemblies are labelled with the suffixes "−1" and "−2", respectively. The cycles in clean water (W samples) were carried out for reference sake, in order to take into account the modification in the mortar mechanical properties due to curing (possibly enhanced by the prolonged permanence in wet conditions and in the oven). All the labels and conditioning procedures are listed in Table 1.

2.4. Characterisation techniques

Flexural and compressive strength tests were performed on mortar according to EN 196-1.

The effects of the salt crystallisation cycles on the assemblies were firstly investigated by visual inspection. Then, in order to determine the mechanical performance of the assemblies, an *ad hoc* shear test was performed. The aim of the test is to assess the behaviour of the interface between brick and mortar by a shear test adapted from the standard UNI EN 1052-3. A 100 kN Galdabini universal testing machine operating in force control at 50 N/s was employed for the specimen loading. Thus, the first part of the load–displacement curve was under study. The displacement of the central prism was measured with respect to the lateral ones by means of a couple of LVDT transducers, as shown in Fig. 3. The choice of the point in the central prism where the displacement is measured, does not influence the results of the shear test. Before shear test, all the assemblies were dried in a ventilated oven at 60 °C up to constant weight, except the SAT samples, which were tested in water saturated conditions. The specimen was positioned in the loading machine with the face previously immersed in the solution at the bottom. Three cardboard leaves, 3 mm thick, were located below and over the specimen in order to reduce localized stress concentrations due to surface irregularities. The load was applied on the top surface of the central prism via an arrangement of 7 mm thick steel plate; no lateral compression was applied. The force was increased up to the collapse of the specimen, that is given by unstable crack propagation at the brick/mortar interface, as it is pursued in this study.

SAT and REF assemblies were tested at the end of the experimental campaign, in order to obtain mechanical and material data comparable to those of the samples altered by the weathering cycles.

After collapse, mortar samples were taken by chisel fragmentation from the mortar layer where failure occurred, as shown in Fig. 4, i.e. at the top (T), centre (C) and bottom (B). Pore size distribution of these mortar samples was determined by mercury intrusion porosimetry (MIP, Porosimeter 2000 Carlo Erba with a Fisons Macropore Unit 120). Moreover, mortar samples were ground to powder (<0.075 mm) and soluble salts were determined by extraction with deionised boiling water (electrical conductivity <0.02 μS), filtration by blue ribbon filter and final ion chromatography (Dionex ICS-1000, equipped with Ion Pac AG14A guard column and Ion Pac AS14A inorganic anion-exchange column kept at 30 °C; measuring cell temperature 35 °C). Before the soluble salt determination, the surface efflorescence were gently brushed away from the top samples (T position in Fig. 4), in order to take into account only the salts within the mortar pores. Soluble salts in the original brick and mortar used for the tests were determined as well, by the same technique.

The morphology and location of salt crystals on the failure surface of the assemblies were observed by stereo-optical microscope (SOM, Wild M3 Heerbrugg) and by scanning electron microscope (SEM, Philips XL 20 equipped by secondary electrons detector) and analysed by EDS detector (Genesis 2000, Philips). Eventually, the mineralogical composition of the weathered SUL-2 mortars was investigated by powder X-ray diffraction (XRD, Philips Diffractometer PW 1840, 40 kV/20 mA, Cu Kα radiation), in order to assess the possible presence of ettringite.