Study of Decay of Historic Masonry Due to Salt Crystallization: A Systematic Approach

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ABSTRACT

The literature concerning the chemical-physical decay and processes of decay of natural building stones subject to aggressive environments is very broad and substantially developed at both the macro and micro structural level. Whereas research carried out on the durability of masonry as a composite material and on the mutual influence of its components (mortar, brick or stone) is much less abundant or advanced and in the 1980’s it was even less developed. The results of research in recent decades have shown that in order to study and understand the decay phenomena due to salt crystallisation and freeze-thaw action, experimental accelerated ageing tests should be carried out on masonry specimens and not on single components. Since the end of the 1970s a Research Unit of the Polytechnic of Milan’s Department of Structural Engineering (DIS) has followed a systematic methodology for the study of damage caused to masonry by salt crystallisation. The decay of masonry is highly influenced not only by aggressive environments but also by the choice and combination of constituents within masonry. Within the DIS group research was initiated by G. Baronio and L. Binda in 1980 [Baronio et al. 1982].

During the initial phase of the research a crystallisation experiment was undertaken, on the basis of state diagrams of the most diffused and harmful salts to masonry components, from which a cyclic ageing test for single masonry components was developed; the experiment had two different aims: (i) ability to study the decay of slender elements such as columns and decorations by total immersion in a salt solution; (ii) study of decay in structural elements having large dimensions by capillary rise of salt solutions where solutions could not typically reach the core of the element. In these experimental studies the specimens were exposed to selected temperature and relative humidity conditions over specified periods of time following uptake of the solution causing decay. The conditioning cycles were repeated until damage to specimens reached a given level [Binda et al. 1985, 1987]. In this manner, the first accelerated ageing tests by capillary rise of salt solutions were proposed for brick and stone.

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Several tests were carried out with different types of salts and different thermo-hygrometric conditions and as well, different duration of conditioning cycles (Fig. 1a, b) [Binda, Charola et al. 1985]. From these studies it was determined that sodium sulphate solution was the most aggressive to brick and stone masonry components over the shortest test duration.

<table>
<thead>
<tr>
<th>Salts</th>
<th>Type of cycle</th>
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<tr>
<td>NaCl</td>
<td>A. $t_1 = 2$ h $t_2 = 46$ h (50% RH)</td>
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<tr>
<td>MgSO$_4$</td>
<td>B. $t_1 = 2$ h $t_2 = 94$ h (50% RH) $t_3 = 166$ h (50% RH)</td>
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<tr>
<td>Na$_2$SO$_4$</td>
<td>C. $t_1 = 2$ h $t_2 = 46$ h (50% RH) $t_3 = 120$ h (60° C)</td>
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<td>D. $t_1 = 2$ h $t_2 = 46$ h (50% RH) $t_3 = 120$ h (100° C)</td>
</tr>
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**Figure 1.** (a)-Different thermo-hygrometric conditions used for different crystallisation cycles; (b)-Percentage of damage refers to the external surface of brick specimens, due to different crystallisation cycles caused by various types of salt solution.

A survey of surface decay on monuments located in Milan has been carried out in which photographs of the surface have been acquired every three to six months since 1981. The natural environment was also studied from which results acquired over 10 years by the Brera Observatory in Milan were evaluated and since 1990 the onsite micro-environment was also monitored near model masonry structures. The data compared with the equilibrium curve of sodium sulphate showed that the formation of its two phases, thenardite and mirabilite, could occur in Milan every month of the year and several times a month with an average duration of 48 hours.

Since a non-destructive technique was required to measure the on-going process of material decay, the research revealed that decay started from the external surface of the material and proceeded, cycle by cycle, toward the interior, the decay often manifesting itself as a delamination (Fig. 2a, b) [Binda et al. 1987]. Furthermore it was found that the material characteristics below the decayed surface remained unaltered (Fig. 2c). Measurements of surface decay were first carried out with gauges applied to the external surface [Binda et al. 1992]. Thereafter, a laser profilometer was adopted as it was determined from studies to be the best tool to precisely measure decay over time (Fig. 3), [Binda et al. 1992].

**Figure 2.** (a)-Decay of historic masonry exposed to the synergetic effects of different decay actions; (b)-Fatigue damage behind brick external surface before delamination; (c) Penetration of decay is shown as only a few millimetres behind external surface damage.

The mutual influence of masonry components on surface damage was first studied on masonry prisms damaged by salt crystallisation [Binda et al. 1985]. From these initial results the decision was then
taken to build full-scale models and subject these to the environmental conditions prevalent of a polluted area of Milan [Baronio et al. 1993]. In order to accelerate the damage process, a sodium sulphate solution was injected into the building foundation so that the ageing could occur by capillary rise of the solution to the masonry structure.

The different types of decay caused to brick masonry by salt crystallisation were defined from work carried out within a European Community (EC) study [Van Balen et al. 1997] and thereafter collected in a “Damage Atlas”. A product of the same study was an expert system (MDDS) on the decay and diagnosis of brick masonry prepared with the aim of helping non expert professionals in the interpretation of decay mechanisms of masonry structures [Van Balen et al. 1997]. Currently, the laboratory crystallisation test that is carried out on masonry prisms forms part of a RILEM recommendation for testing as proposed by the TNO-Delft and the results have been calibrated in three EC studies in which other partners have also participated [RILEM 1998].

A more sophisticated device was introduced to measure surface decay: the laser profilometer. This device uses a laser beam that scans the surface of the materials and is thus able to characterise the variation in surface profile of a material. A suitable data acquisition system transforms these measurements to surface roughness profiles that in turn can be modified to describe the decay as a function of time and space (Fig. 3). The values of the chosen parameter measured over time can constitute the input data for a deterministic or probabilistic mathematical model in which material behaviour and durability of surface treatments in the presence of different soluble salts and exposed to salts of different concentration can be studied [Cardani et al. 2002]. The high degree of randomness associated with acquiring the material characteristics and their level of decay when subjected to natural ageing conditions suggests that the deterioration process may be defined, for example, by a function $L(t, l)$; hence this is a stochastic process having random variables $l$ and $t$, where $l$ is the loss of material at the surface in time $t$ (Fig. 4) [Garavaglia et al. 2002].

In order to model this decay function of material loss, a log-normal probability density function was chosen. Whereas, the deterioration process can be treated as a reliability problem in which the time to achieve a specified, yet significant degree of damage $l$ is determined and as well, the variation in time needed to exceed it. In this way, for different damage levels $l$ it is possible to develop a vulnerability to decay curve for each degree of damage $l$ (Fig. 4c). A vulnerability to decay curve describes the probability of reaching or exceeding a given damage $l$ over time. In order to model the vulnerability to decay curves obtained experimentally, a Weibull distribution was chosen as in fact, this type of distribution appears to provide a good interpretation of the physical phenomenon. This approach was used not only to model decay mechanisms, but also to reduce the time required in completing ageing
tests and thus prevent the occurrence of decay, particularly when using surface treatments and material substitutions. The results of these research studies can help in making choices of appropriate repair and protection techniques for external surfaces of historic masonry buildings.

**Figure 4.** (a)-Brick specimen treated with water repellent and damaged by crystallisation test with a concentration of 2.5% of Na₂SO₄ after cut; (b)-Interpolation of the curve loss area/time for modelling of the decay process L(t*,τ); (c)-Vulnerability to decay curves for same masonry specimen.

**REFERENCES**


Binda L., Charola A.E., Baronio G. 1985, ‘Deterioration of porous materials due to salt crystallization under different thermohygrometric conditions’, 5th Int. Conf. on Deterioration and Conservation of Stone, Lausanne, Suisse, pp. 279-288.


