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A Probabilistic Model to Predict the Durability of Surface Treatments

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Abstract

Water repellent or consolidating surface treatments for brick and stone facing walls cannot be carried out in presence of salts due to the possible formation of cryptoefflorescence. Nevertheless, an attempt has been made within an EC contract, to establish the maximum salt content below which the surface treatments does not fail. Crystallization tests were carried out on treated and non-treated masonry materials and a suitable damage parameter describing the material deterioration process has been chosen. The parameter assumed is the loss of surface material at each measurement carried out with a laser device along chosen profiles on the sample surface. Some results of the on-going tests are presented. The high randomness connected with the material characteristics and decay in a natural environment suggests assuming the deterioration process $L(\lambda)$ as a stochastic process of the random variable λ (where λ is the loss of surface material). Consequently, the probability of reaching or exceeding a given damage $\bar{\lambda}$ over time can be described by the corresponding fragility curve. By using this approach the magnitude of the expected damage over time as well as the occurrence time can be predicted.

1 Introduction

Salt decay is one of the most frequent causes of deterioration encountered in masonry walls. The presence of water in the walls, due to capillary rise and/or rain penetration, is the vehicle through which soluble salts are distributed in the material. Evaporation takes the salts toward the exposed surfaces of the walls; salts crystallising behind the surface cause delamination and crumbling of the masonry components. Water repellent or consolidating surface treatments cannot be carried out in presence of salts due to the possible formation of cryptoefflorescence. A research at European level supported by the EC has been carried out with the aim of establishing the maximum salt content, below which surface treatments do not fail. Crystallization tests were carried out on treated and non-treated masonry materials. The materials used are: 4 different natural building stone units and 1 type of clay unit. Three types of salt solutions were used and each with four different low percentages of salt concentration.

On the basis of recorded experimental data, a suitable damage parameter describing the material deterioration process has been chosen. The parameter assumed is the loss of surface material at each measurement. The measurements have been made through a laser device along chosen profiles on the sample surface. Therefore, the loss of surface material was quantified as the variation of the profile depth over time.

The high randomness connected with the material characteristics and decay level in a natural environment, suggests assuming the deterioration process $L(\lambda)$ as a stochastic process of the random variable λ (where λ is the loss of surface material). The deterioration process could be interpreted as a stochastic process $L(t,\lambda)$, function of time t and damage λ. Considering a given significant damage $\bar{\lambda}$ and the variable time needed to exceed it; the deterioration process can be treated as a reliability problem. Indeed, reliability R(t) is concerned with the performance of a system over time and it is defined as the probability that the system does not fail by time t. This definition can be extended by denoting $\bar{R}(t)$ as the probability that a system exceeds a given significant damage threshold $\bar{\lambda}$ by time t. The random variable that is used to quantify reliability is $\bar{T}$, the time to exceed damage $\bar{\lambda}$. As a consequence, the fragility curve for each $\bar{\lambda}$ can be defined. A fragility curve describes the probability of reaching or exceeding a given damage $\bar{\lambda}$ over time.

By using this approach the magnitude of the expected damage over time as well as the occurrence time of the damage can be predicted.

In Sec. 5 the application of this procedure is presented and the results concern the quantification of the loss of surface material over time. The fragility curves can be drawn only at the end of the laboratory tests, because more measurements are necessary. In Sec. 6 the efficacy of surface treatments on different materials in presence of different salts at different concentrations is discussed.

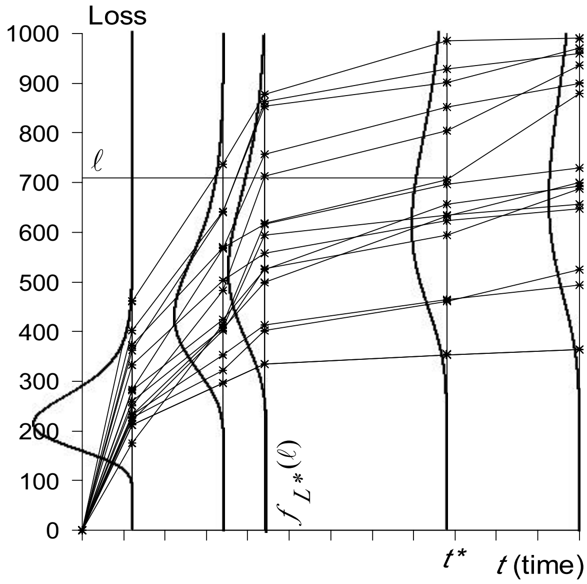

Figure 1: Experimental loss diagram (*) and the modelling of the deterioration process L(t,λ)

2 The deterioration process as a stochastic process in the r.v. λ

Provided that the parameter measuring the decay has been chosen it has been shown [1] that the deterioration process will be interpreted as a stochastic process L(t,λ), function of time t and damage λ, where λ is considered a r.v.; experimental evidence. However for a given time t* (e.g. each instant of measurement of damage) the deterioration process can be viewed as function of the r.v. λ only (e.g. the loss of surface material at the time t*; it will be different from sample to sample); thus we use the notation L*(λ) in order to denote the deterioration process at any given fixed time t*. The probability density function (p.d.f.) $f_{L*}(\lambda)$ can be modelled as a Log-Norm p.d.f. (Fig. 1.) [1]

On the other hand, we can consider a given significant damage threshold $\bar{\lambda}$ and the variable time needed to exceed it; thus the deterioration process can be treated as a reliability problem. Indeed [2] the reliability R(t) is concerned with system does not fail by time t. Here we extend this definition denoting by $\bar{R}(t)$ the probability that a system exceeds a given significant damage threshold $\bar{\lambda}$ by time t. The random variable that is used to quantify the reliability is $\bar{T}$ which is just the time to exceed the threshold $\bar{\lambda}$. Thus, from this point of view, the reliability function is given by

$$\bar{R}(t) = Pr(\bar{T} > t) = 1 - F_{\bar{T}}(t) \qquad (1)$$

where $F_{\bar{T}}(t)$ is the distribution function for $\bar{T}$. Assuming that the density function $f_{\bar{T}}(t)$ exists for the r.v. $\bar{T}$, the hazard rate function h(t) is given by:

$$h_{\bar{T}}(t) = \frac{f_{\bar{T}}(t)}{\bar{R}(t)} \tag{2}$$

Computing $F_{\bar{T}}(t)$ for different damage levels $\bar{\lambda}$ allows us to build the fragility curve for each $\bar{\lambda}$.

A fragility curve describes the probability of reaching or exceeding a given damage $\bar{\lambda}$ over time [3]. For a particular damage level $\bar{\lambda}$ at a given time t*, the reaching probability can be seen as the area under the threshold $\bar{\lambda}$ and the exceeding probability can be seen as the area over the threshold $\bar{\lambda}$ (Fig. 2). Indeed, the computed areas over different thresholds $\bar{\lambda}$ provide the experimental data used to fit the fragility curves (Fig. 3). Therefore, the evaluation for different t* of the exceeding probability, connected with each damage level $\bar{\lambda}$, leads to obtain an experimental fragility curve for each chosen $\bar{\lambda}$.

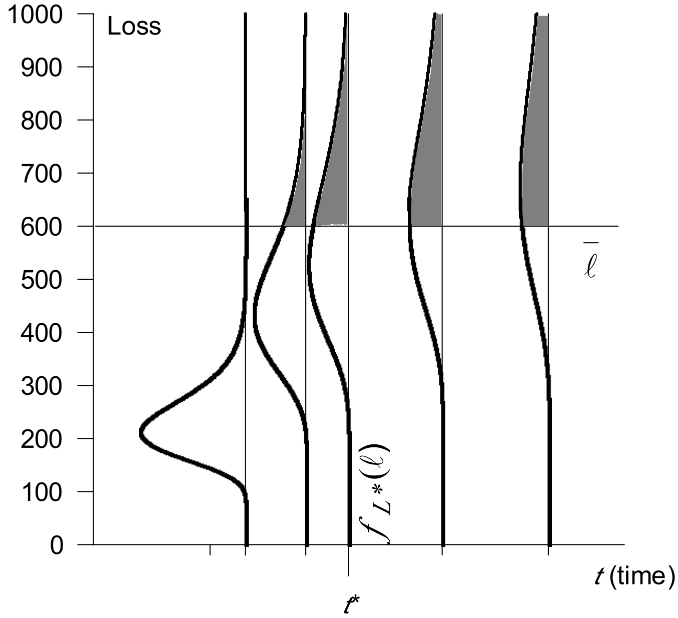

Figure 2: Exceedence probability to cross the threshold λ

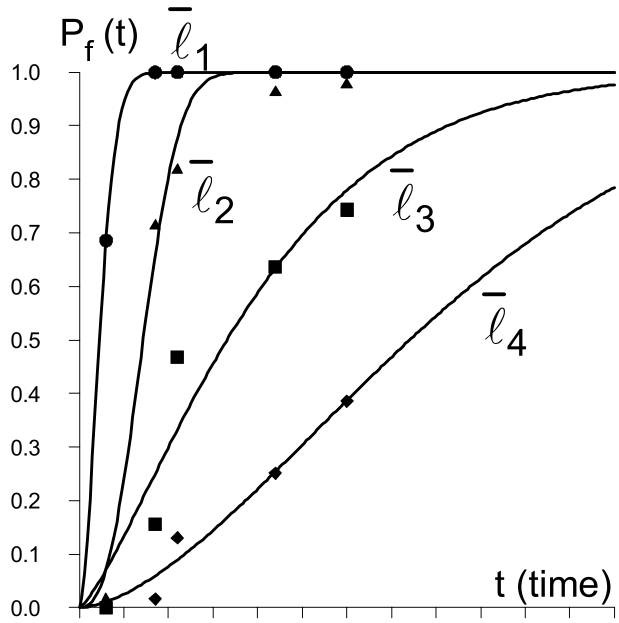

Figure 3: Example of fragility curves for different λ

In order to model the experimental fragility curves, a Weibull distribution has been chosen [1, 4, 5,]. In fact this distribution seems to give a good interpretation of the physical phenomenon as it has been demonstrated in [6].

In predicting the exceeded probability of loosing a certain quantity of surface material (i.e. the treated surface layers) over time, the fragility curves could be useful to plan maintenance strategies and to evaluate durability and efficiency of surface treatments.

The first part of the procedure introduced here has been applied on the results of new laboratory tests made at the Department of Structural Engineering, Politecnico of Milan under the EC contract ENV4-CT98-0710. (see Sec. 3-5). The fragility curves will be built at the end of the tests, which are still in progress.

3 Experimental research

3.1 Single substrates

Crystallization tests were carried out, according to [7], on one type of softmud brick, three different natural building stones, with supposedly similar porosities: (a) tuff stone from the Netherlands, (b) Savonnière stone from France, (c) Noto

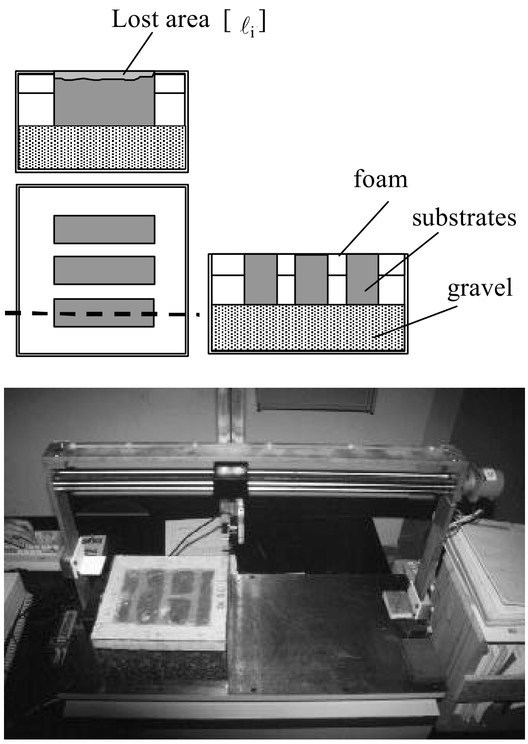

Figure 4: Laser profilometer device during measurement and a box scheme

Table 1: Single substrates properties

Material	Physical properties				Tensile strength	
	C.M.C (w%)	Capillarity coeffic. ($g \cdot cm^2 \cdot h^{-0.5}$)	water abs. (w %)	porosity (vol.%)	σ_t dry	σ_t wet
Tuff stone	27.64	2.96	33.15	43.65	1.33	0.61
Noto stone	12.87	0.75	15.65	29.04	2.82	1.32
Savonnière	9.47	0.34	11.31	18.82	1.35	0.95
Serena	0.57	0.25	1.99	5.19	6.83	3.54
Softmud Brick	21.70	2.10	23.09	35.70	0.93	0.89

Table 2: Amount of salts as weight percentage of the dry specimen introduced in each treated and untreated specimen.

Salt referred to CapMC	1%	2.5%	5%	7.5%
Salt solution	12.50 g/l	31.25 g/l	62.50 g/l	93.75 g/l
% of the dry specimen	0.28	0.69	1.38	Tuff stone
	0.13	0.32	0.64	Noto stone
	Savonnière	0.24	0.47	0.71
	Serena	0.01	0.03	0.04
	0.22	0.54	1.08	Softmud brick

limestone from Italy; and, a stone with lower porosity, the Serena sandstone from Italy.

The crystallization test described in [7] concerns masonry prisms. In this research the same test was used to study single material. The extension was simple, since the boxes used for the normal test were easily adapted to contain 3 specimens of single materials (Fig. 4). Before starting the crystallization test, the units were subjected to different physical and mechanical tests (see Table 1) in order to choose the quantity of salt solution to be introduced to each specimen.

3.2 Salt solution

Three different salts were chosen among the most diffused in Italy: Sodium sulphate (Na_2SO_4), Sodium Chloride (NaCl) and Magnesium sulphate ($MgSO_4$). According to the EC contract, the salt concentration depends on the capillary moisture content (CapMC) which is calculated on the basis of the water absorbed for capillary rise in 48 hours. In each specimen an amount of the 80% of the CapMC was introduced, according to [7], with different salt concentrations for each type of salt, as reported in Table 2.

So 45 different situations of treated units were obtained and other 45 of untreated units as reference.

3.3 Surface treatment

One type of treatment was used on the surface materials before inserting the salt solutions: a water based water repellent (Wacker 1311) with a capillary absorption of 10”. The choice of this water repellent is suggested by its common use.

4 Application of the procedure on the crystallization test results

The deterioration process of each specimen was recorded in three different ways: a) with a visual inspection; b) photographically and c) with a laser profilometer (Fig. 4).

The use of the laser profilometer allows for measuring, with very good resolution, the loss of material calculated on the specimens exposed surface at subsequent times [8].

Subsequent measurements show how the loss changes over time due to the progress of the surface decay. In this way it is possible to monitor the material loss with time. Figure 5 shows an example of diagram for the first measurements made.

The presence of swelling phenomenon can compromise the damage measurements. Since bulging is the previous step before detachment, it is possible to consider it as the starting point of a damage. Therefore, through a simple model the experimental measurements have been converted in new deterioration diagrams where bulging has been eliminated [1].

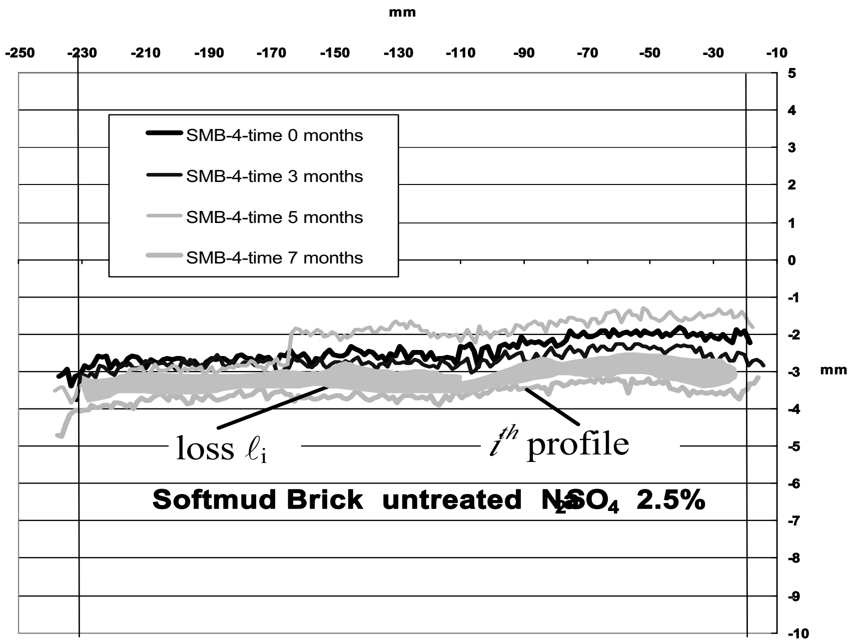

Figure 5: Example of diagram for the first measurments made with laser profilographer on one single specimen

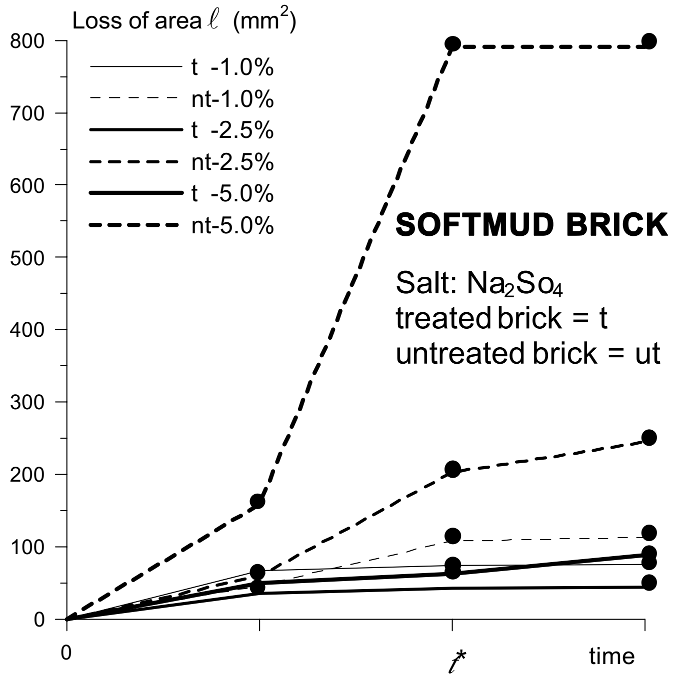

Figure 6: Deterioration vs. time: example of damage diagram on a series of specimens

The loss of material seems to be a good parameter to quantify the masonry damage due to salt crystallization and it can be well quantified using these new diagrams. Therefore, for each profile *i*, represented in Fig. 5, the loss λ_i of the specimen heigh calculated over the cross section (in mm^2), calculated at every time t^* of measurement (t^*=3, 5, 7 months), has been assumed as parameter of damage. At every time t^*, in order to quantify λ_i, the area included between two consecutive diagrams is assumed. This area is automatically calculated by the computer program developed to eliminate bulging [1].

In Fig. 6, for each profile *i*, the plot of the damage λ_i versus time is reported. A simple interpolation of the experimental points permits to better read the behaviour of the loss over time (linear splines). In a second time, as mentioned in section 2, when the data will be sufficient for a probabilistic analysis, at every t^* the loss can be modelled with a lognormal distribution, and the fragility curves evaluated.

5 Evaluation of the results

5.1 Remarks

The results obtained by modelling the experimental data with the procedure presented in Sec. 2. will be, now, discussed. The threshold $\bar{\lambda}$ for the material is considered 0.5 %.

5.2 Quantification of the decay over time

Softmud-Brick: after 7 months, the treated single clay units do not show any visible damage for all the three salt concentrations for each of the three types of salt (Fig. 7 *a, b, c*). The exfoliation is serious in the *untreated* bricks for the 2.5% and 5% of Na_2SO_4 concentrations and it is at its beginning for the highest concentration of NaCl and $MgSO_4$. The 1% of Na_2SO_4 and the 1% and 2.5% of NaCl and $MgSO_4$ for *treated* and *untreated* units seem to be the salt concentrations below which surface water repellent treatment could be carried out without affecting the durability of the single materials.

Tuff Stone: this stone, both *treated* and *untreated,* is more sensible to $MgSO_4$ than to the other salts, although the decay is serious also for Na_2SO_4 (Fig.8 *a, b, c*). In the case of $MgSO_4$ the complete detachment of the *treated* layer was observed after 5 months for the 5% concentration, and after 7 months for the 2.5% concentration. The numerous inclusions are the weak point of this material: the decay starts from these points already at the lowest concentration. This means that it is suggested not to treat this stone in presence of salts.

Noto Stone: delaminated stone surfaces are visible in many specimens, both *treated* and *untreated* (Fig. 9 *a, b, c*). Observing in Fig. 9a the effect of the Na_2SO_4, it is really suggested to avoid surface treatments, at any salt concentration. The damage for the other two types of salts is only delayed and so expected.

Savonnière Stone: in the case of Na_2SO_4 with 7.5% and 5% of salts, it is clearly shown in Fig. 10 *a*) that it is unnecessary to submit the stone to surface treatment. The increase of decay in the untreated units leads to believe that the damage of the treated units can be delayed but is soon to be expected. Sensitiveness is shown also to $MgSO_4$ (Fig. 10 *c*).

Serena Sandstone: no interesting plots were obtained due to the absence of the decay in these stone units. Only after 10 months it is visible a small whitish layer of efflorescences on the untreated stones only.

Comparing the decay in laboratory of single units with the one recorded on full-scale models outdoors [9], it was clear that, even if the stone has low porosity, with the presence of mortar, the decay is accelerated. Also in this case water repellent treatments may not be appropriate.

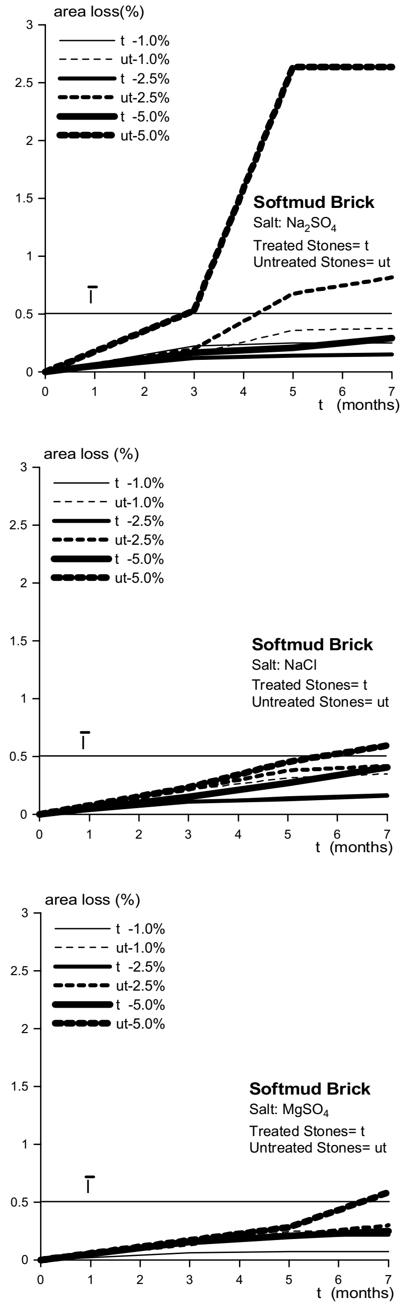

Figure 7: Softmud-Brick: deterioration plots for three types of salts

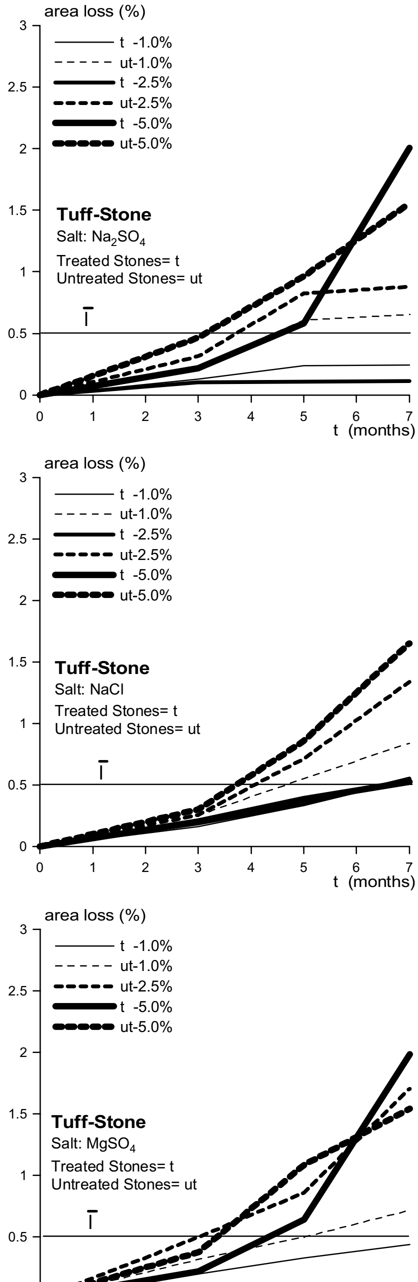

Figure 8: Tuff stone: deterioration plots for the three types of salts

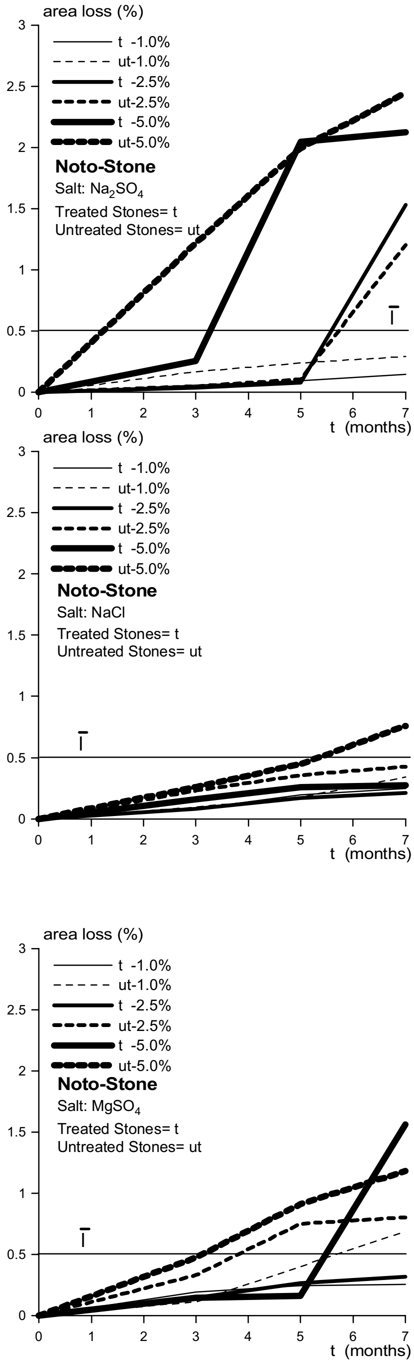

Figure 9: Noto Stone:deterioration plots for the three types of salts

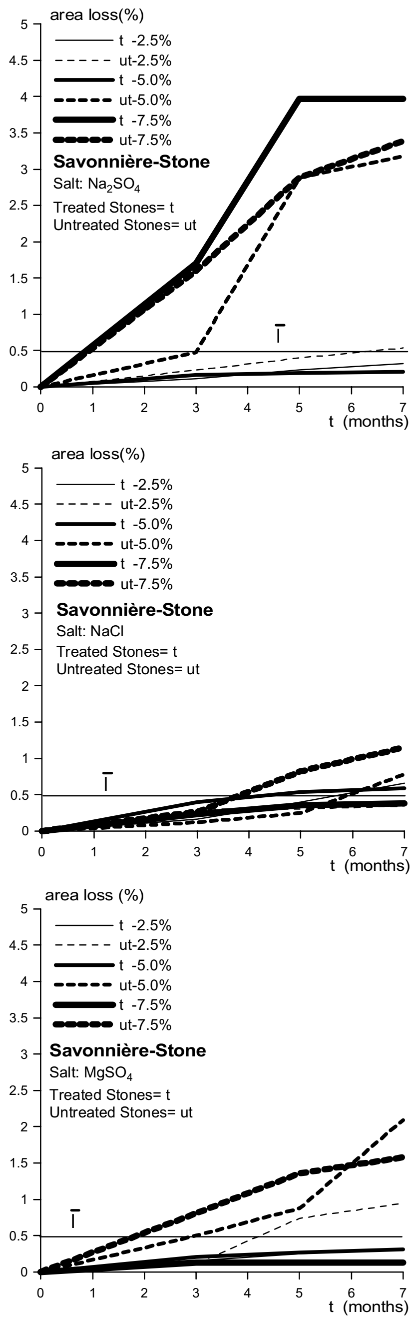

Figure 10: Savonniére Stone: deterioration plots for the three types of salts

5.3 Fragility curves

As reported in Sec.2, the decay process of a building material subjected to aggressive attack is affected by randomness. Therefore, at each t^* measurement the surface material loss l is random. For its modelling, in Sec.2 a lognormal p.d.f. was proposed requiring a sufficiently representative number of homogeneous specimens [1]. At the moment the available data do not allow for the elaboration of the p.d.f.. As building the fragility curves depends on the p.d.f., the second part of the application of this modelling will be postponed till the end of tests. They could be useful to evaluate durability and efficiency of surface treatments. However, already with this first elaboration, some prediction on the efficiency of the used treatment could be given.

5.4 Some remarks

From the results obtained it is possible to make some general remarks:

- A different behaviour was observed between the treated natural building stones and the bricks at the same testing time due to their different nature and physical characteristics. After 7 months, the treated bricks show do not show any damage yet, while for stones, the treated layer detached completely. For the bricks, this could be due to the sufficiently low concentration of salt.
- The lowest salt concentration (1%) did not cause any damage to the treated specimen. However, damage to the untreated ones was starting at this time. Therefore, since in many cases treatments only show a delay in the appearance of damage, it is possible that at longer times even the treated specimens will show some damage;
- For the other two concentrations the damage was always present for all the specimens and salts even if to a different extent and at different times. Therefore when salt concentrations such as these are present, treatments should not be done.
- The onset of delamination on the stones surfaces does not seem to be directly connected with the tensile strength of the stones, but rather with their porosity. In fact the damage is firstly visible on the most porous stone (as in the Tuff stone case). This also means that tensile strength is not linearly correlated to porosity.
- Generally the Sodium Sulphate is known to cause the maximum damage, but depending on the stone composition, other salts can be more destructive, e.g. the behaviour of the Tuff stone with Magnesium sulphate.

The laboratory tests were carried out under controlled condition of temperature and R.H.. These conditions are variable on site, in addition only one type of salt was used per specimen, therefore the obtained results could not be observed in situ.-

6 Conclusion

In the contest of an EC Contract the procedure presented in the previous sections has been applied to 4 types of different stone masonry units and 1 type of clay masonry unit untreated and treated with a water repellent agent (W1311). The specimens have been subjected to accelerated laboratory test of salt crystallization, with 3 different types of salt.

A modelling procedure, applied in its first part, has served to evaluate the efficiency of a surface treatment on different building materials, in presence of different salts and at different concentrations. For the considered testing time, the results have shown that the efficiency of the water repellent treatment is quite satisfactory on artificial clay units but not on the here tested natural building stones. In this case the detachment of the treated layer happens in a really short time leaving the material again untreated. These results however represent the behaviour only of the single units and not their behaviour in the mortar/units system. In fact the observed and measured damage on the brick and stone masonry, particularly on site, could be totally different.

7 References

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