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Prediction of the Service Life of Brick/Stone Masonry Damaged by Salt Crystallisation: Application of a Stochastic Model

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ABSTRACT

An attempt has been made within a EC Contract, to establish the maximum salt content in brick and stone masonry, below which the surface protection treatments do not fail. Crystallisation tests were carried out on treated and untreated brick and limestone masonry specimens. A large number of tests were previously carried out on the single units used for the masonry specimens. Salt solutions with two low concentrations of sodium sulphate were inserted in masonry wallettes treated with a water based water repellent or with a consolidant. On the basis of the recorded experimental data, a suitable damage parameter describing the material deterioration process has been chosen. The parameter assumed is the loss of surface material. The deterioration process could be interpreted as a stochastic process $L(t,\ell)$, function of time t and damage ℓ. In this way, for different damage levels $\overline{\ell}$ it is possible to build the fragility curve for each $\overline{\ell}$. By using this approach the magnitude of the expected damage over time and the occurrence time of it can be predicted. The results will allow for the investigation on the durability of materials with respect to the prediction treatments and on the decay process of single and composite materials.

KEYWORDS

Salt crystallisation, masonry decay, stochastic processes, fragility curves, durability prediction.

INTRODUCTION

In an aggressive environment, one of the most important causes of deterioration for the masonry is the salt crystallisation. The presence of moisture in the walls, due to capillary rise, rain penetration or else, is the vehicle through which soluble salts are distributed in the material. The water evaporation phenomenon takes the salts toward the external surface of the wall; salts crystallising behind the surface causes delamination and/or crumbling of the masonry components.

Water proof or consolidation surface treatments can be dangerous in the presence of salts due to the possible formation of cryptoefflorescence under the treatment. Crystallisation tests were carried out on treated and non-treated masonry materials. The masonry units were: 4 different types of natural building stones and 1 type of brick. Three types of salt solutions were used and each with four different low percentages of salt concentration. It was not used a saturated salt solution as recommended by the code, because the aim was to define a salt crystallisation threshold for treatments. The treatment used was a water based water repellent largely used. As the durability of masonry as a composite should be taken into account, crystallisation tests were carried out also on treated and untreated brick and stone masonry prisms. Salt solutions with two low concentrations of sodium sulphate were inserted in the wallettes treated with the same water based water repellent, used for the single substrates, and a consolidant.

On the basis of the 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 surface masonry. Therefore, the loss of surface material is quantified as the variation of the profile depth over time. The high randomness connected with the material characteristics and decay in a natural environment suggests to assume the deterioration process L(ℓ) as a stochastic process of the random variable ℓ (where ℓ is the loss of surface material). The deterioration process can interpreted as a stochastic process L(t,ℓ), function of time t and damage ℓ, where ℓ is considered a random variable (r.v.) because of the experimental evidence. However, for a given time t^* the deterioration process can be viewed as function of the r.v. ℓ only; therefore the process can be modelled with a probability density function (p.d.f.) L(t^*,ℓ) depending only on ℓ. To model it a Log-Normal p.d.f. was chosen. For the model, a significant threshold of the damage $\overline{\ell}$ has to be defined and the variable time needed to exceed it can be considered; thus the deterioration process can be treated as a reliability problem. In this way, for different damage levels, $\overline{\ell}$ allows for building the *fragility curve* for each $\overline{\ell}$. A fragility curve describes the probability of reaching or exceeding a given damage $\overline{\ell}$ over time. By using this approach the magnitude of the expected damage over time and the occurrence time of it can be predicted.

A PROBABILISTIC MODEL FOR THE PREDICTION OF THE DAMAGE

Once the parameter measuring the decay has been chosen, it has been shown in (Garavaglia *et al.* 2002*a*), from experimental evidence that the deterioration process can be interpreted as a stochastic process $L(t,\ell)$, function of the time t and of the damage ℓ, where ℓ is considered a random variable (r.v.). However, for the given time t^* (e.g. each instant of damage measurement) the deterioration process can be seen as a function of the r.v. ℓ only (e.g. the loss of surface material at the time t^*, which will be different from sample to sample); thus the notation $L^*(\ell)$ is used to indicate the deterioration process at any given fixed time t^*. The probability density function (p.d.f.) $f_{L^*}(\ell)$, describing the behaviour of ℓ at the time t^*, can be modelled as a Log-Normal p.d.f. (Fig.1) (Garavaglia *et al.* 2002*a;*, Binda *et al.* 1999*a*). On the other hand, it is possible to consider a given significant damage threshold $\overline{\ell}$ and the variable time needed to exceed it; thus the deterioration process can be treated as a reliability problem. Indeed the reliability $R(t)$ concerns with the performance of a system over time and it is defined as the probability that the system does not fail by time t (Evans 1992). Here this definition is extended denoting by $\overline{R}(t)$ the probability that a system exceeds a given significant damage threshold $\overline{\ell}$ by time t. The r.v. that is used to quantify the reliability is $\overline{T}$ which is just the time necessary to exceed the damage threshold $\overline{\ell}$. Thus, from this point of view, the reliability function is given by

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

where $F_{\overline{T}}(t)$ is the distribution function for $\overline{T}$.

Computing $F_{\overline{T}}(t)$ for different damage levels $\overline{\ell}$ allows for obtaining a *fragility curve* for each $\overline{\ell}$. A fragility curve describes the probability of reaching or exceeding a given damage $\overline{\ell}$ over time (Garavaglia et al. 2002a; Garavaglia & Pavani 2001).

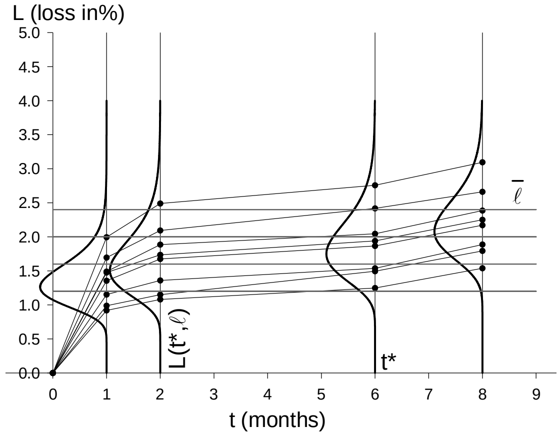


Figure 1. Interpolation of a loss diagrams (∗) and the modelling of the deterioration process L(t*,ℓ)

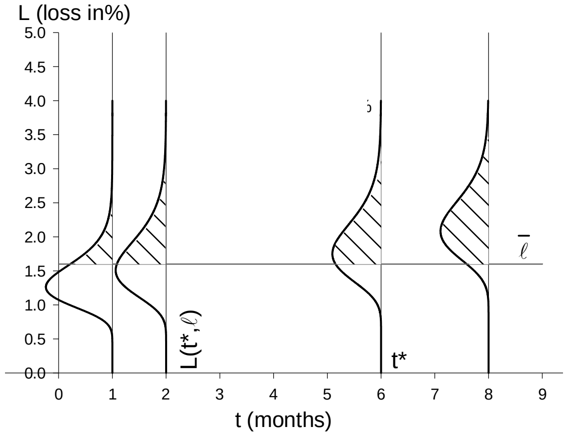


Figure 2. Exceeding probability to cross the threshold $\bar{\ell}$

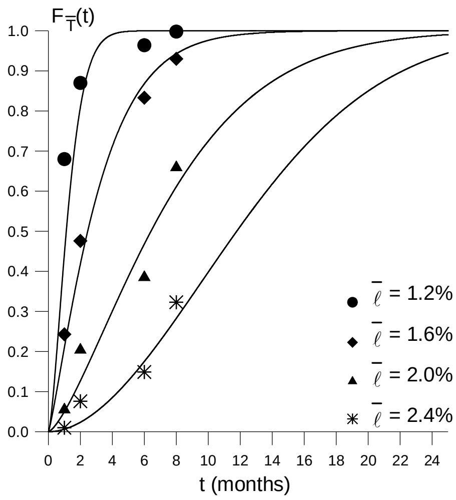


Figure 3. Example of fragility curves for different $\bar{\ell}$

For a chosen damage level $\bar{\ell}$ at a given time *t**, the probability to reach $\bar{\ell}$ can be seen as the area below the threshold $\bar{\ell}$ and the probability of exceeding it can be seen as the area above the threshold $\bar{\ell}$ (Fig. 2). Indeed, the computed areas over different thresholds $\bar{\ell}$ provide the experimental data used to build the experimental fragility curves (Fig. 3). Therefore, the evaluation for different *t** of the exceeding probability, connected with each damage level $\bar{\ell}$, leads to obtain an experimental fragility curve for each chosen $\bar{\ell}$. In order to model the experimental fragility curves, a Weibull distribution has been chosen (Carnmer & Richerson 1998; Bekker 1999). In fact this distribution seems to be a good interpretation of the physical phenomenon as it has been demonstrated in (Garavaglia et al. 2002a). The model applied to the case of surface treatment allows to predict the exceeded probability of a threshold damage over time. The fragility curves could be useful to plan maintenance strategies and to evaluate durability and effectiveness of surface treatments.

MEASURE OF THE DAMAGE: LABORATORY INVESTIGATION

Salt crystallisation tests were carried out at the Department of Structural Engineering, Politecnico of Milan under the EC contract ENV4-CT98-0710 on masonry units (Cardani *et al.* 2001*a*) and on masonry prisms (Cardani *et al.* 2001*b*; Cardani *et al.* 2002) in order to establish the maximum salt content, admissible for treatments. The test on masonry units was carried out first to compare the effect of different type of salts and salt concentrations in order to find the damage threshold. In the last decade it became clear the limit of tests on single materials, when it is necessary to predict the durability of a masonry. It was in fact found by the authors already in 1985 (Binda & Baronio 1985), that the choice of mortar and the brick has a large influence on the durability of brick masonry under salt crystallisation decay, this according to the porosity characteristics of the two materials, when combined in a wall. Therefore a crystallisation test on wallettes was then carried out. The test was set up by TNO (Delft, NL) and included in the RILEM TC127MS Recommendations (Rilem 1998).

Masonry Units

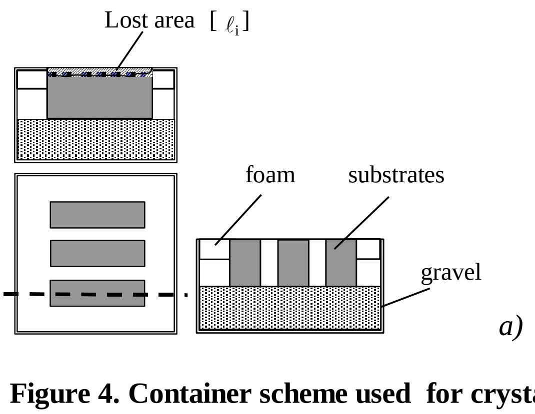
Salt crystallisation tests were carried out, according to RILEM TC127MS Recommendations in (Rilem 1998), on one type of softmud contemporary brick used for restoration and on four different natural building stones: (a) tuff stone from the Netherlands, (b) Savonnière stone from France, (c) Noto limestone and d) Serena sandstone from Italy. Before starting the crystallisation test, the units were subjected to different physical tests in order to choose the quantity of salt solution to be inserted in each specimen and to mechanical tests, as reported in table 1. For this part of the research three different salts were chosen among the most diffused in Italy: Sodium sulphate (Na_2SO_4), Sodium Chloride (NaCl) and Magnesium Sulphate ($MgSO_4$).

Table 1. Single substrates properties

Material	*Physical properties*				*Tensile strength*	
	CapMC (w%)	*Capillarity coeffic. ($g \cdot cm^2 \cdot h^{-0.5}$)*	*Water abs. (w %)*	*Porosity (vol.%)*	$\sigma_{t\ dry}$ *(N/mm²)*	$\sigma_{t\ wet}$ *(N/mm²)*
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

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 with three different salt concentrations for each type of salt: 1%, 2.5% and 5% of CapMC, referred to the % of weight of the dry specimen. For the stone units with a low porosity (Savonnière stone and Serena sandstone) the lowest salt concentration of 1% was substituted with a higher one of 7.5%. One type of treatment was used on the material surface, by immersing the upper surface into treatment for 10 seconds, before inserting the salt solutions: a water based water repellent, a solventless silicone microemulsion concentrate based on silanes and siloxanes, diluted with water to yield microemulsion. The choice of this water repellent is suggested by its large use. So 45 different situations of treated units were obtained and other 45 of untreated units as reference. The crystallisation test described in (Rilem 1998) concerns masonry prisms, but in this research the same test was used to study before the single materials. The extension was simple, since the boxes used for the normal test were easily adapted to contain 3 specimens of single materials (Fig.4*a*, *b*).

The specimens were put in contact with their back side with a salt solution at a chosen concentration and then stored over a layer of dry gravel in a plastic container (open at the top) with the upper face exposed to the environment (controlled laboratory environment of 20°C and 50% R.H.). Demineralized water was added, when approximately the specimens were approaching the constant mass in order to start a new cycle and to accelerate the damage.



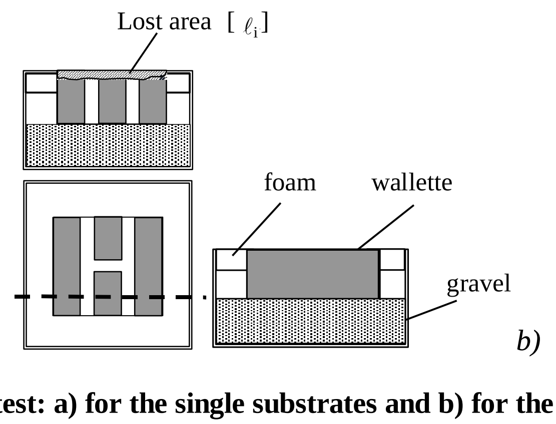


Figure 4. Container scheme used for crystallisation test: a) for the single substrates and b) for the wallettes

Masonry Wallettes

Crystallisation tests were carried out on masonry wallettes (250x200x120 mm) made with the same type of softmud brick and on three of the natural building stones: Noto limestone, Savonnière stone and Serena sandstone. The wallettes were all realised with bedding joints, 15 mm high, made with a mortar based on putty lime. In each specimen an amount of salt solution was introduced, according to (Rilem 1998), with different salt concentrations of Na_2SO_4: 1% and 2.5% of Cap.MC, as for single substrates, and referred to the % of weight of the dry specimen. These percentages are the lowest salt concentrations used for the single units, chosen also for the wallettes in order to verify whether or not these values can still be considered as a threshold value for the masonry. Before inserting the salt solution, part of the wallettes were treated with a water based water repellent and part with a consolidant by immersing the upper surface into the treatment for 10 sec for the water repellent and 30 sec for the consolidant. One wallette for each material was left blank to be used as reference. The water repellent was the same used for the single units. The consolidant mainly consists of reactive silicic acid ethyl ester compounds. The choice of these treatments was suggested by their large use. The same procedure described for single masonry units was used (Fig.4).

Measure of the Damage as a Function of Time

Each four weeks the specimens were subjected to: a) photographic survey; b) cleaning from efflorescences and detached material with soft brush and a vacuum cleaner; c) again photographic survey; d) description of the observed damage, e) surveying of the surface profiles by means of the laser profilometer allowing for a quantitative measurement of the surface decay. The chosen test tries to represent the crystallisation phenomenon in a real exposed wall. The formation of efflorescence and sub-florescence is connected to the migration of the salt solutions toward the surface following water evaporation. A laser profilometer (Fig.5) was used to monitor the damage on the masonry surface (Enel/Cris 1989). The use of the laser profilometer allows for measuring, with a very good resolution, the loss of material in a chosen positions from the exposed surface calculated at subsequent times. Subsequent surveyed profiles show how the surface is changing over time due to the progress of the decay and the loss of material can be measured. Figure 6 shows an example of diagram for the measurements made. The salt crystallisation produces high stress inside the material; the effect is a continuous crumbling and delamination of the exterior surface of the wall while the inside is left unaltered.

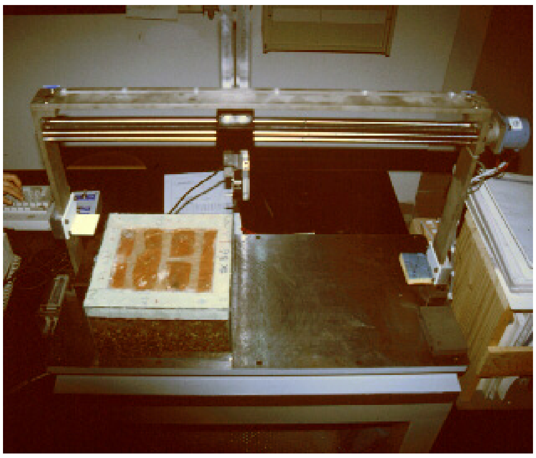


Figure 5. Laser profilometer device during measurement

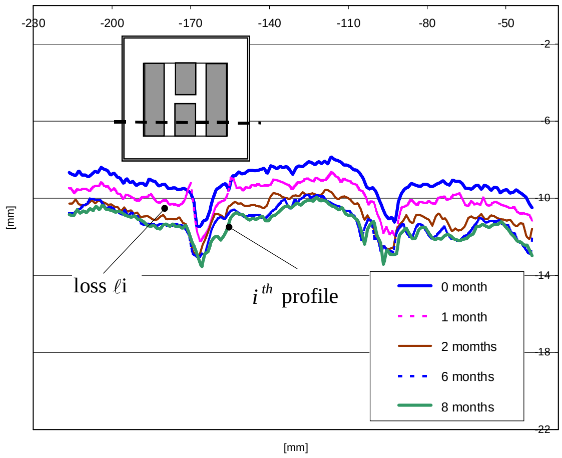
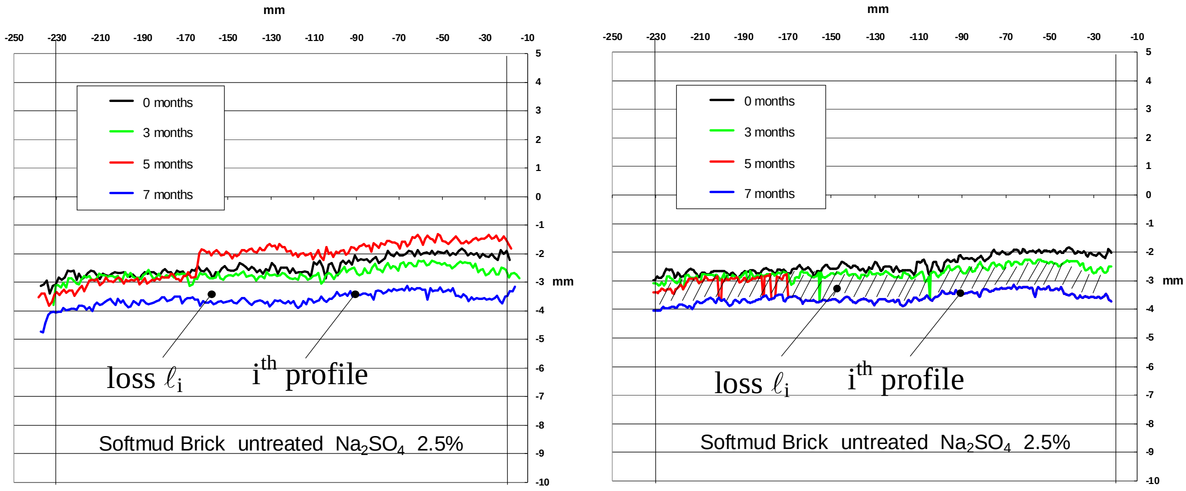


Figure 6. Example of the first measurements realised with laser profilometer on one wallette

For this reason the variation in roughness of the surface has been assumed as measure of the damage occurred to the masonry. The presence of swelling phenomena compromises the damage measurements (Fig.7*a*). Since bulging is the previous step before detachment, it is possible to consider it as the starting

point of a damage. For each profile *i*, represented in Fig.7*a*, the loss ℓ_i of cross section of the wall (in mm^2), calculated at every time t^* of measurement (t^*= 1, 2, 6, 8 months), has been assumed as parameter of damage for the decay due to salt crystallisation. At every time t^*, to quantify ℓ_i, the area included between two consecutive diagrams is assumed (Fig.7*b*). This area is automatically calculated by the computer code studied to eliminate bulging (Garavaglia *et al.* 2002*a*).
In order to compare all the results obtained, the damage has been plotted in percentage:

$$p = \frac{\text{area lost}}{\text{total area of the section}} * 100 \qquad (1)$$



a) *b)*

Figure 7a, b. Example of deterioration measurements over time a) before and b) after the swelling has been removed on a unit of the masonry specimen.

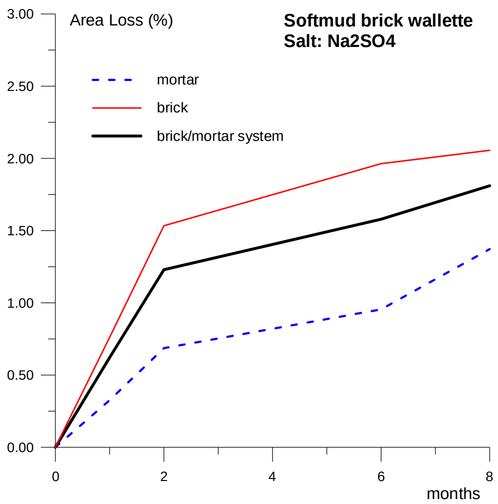


Figure 8. Deterioration vs. time: example of damage on an untreated brick-wallette

A simple interpolation of the experimental points allows to better read the behaviour of the loss over time (linear splines). In Figure 8 the area loss (%) of brick, mortar and brick/mortar system is reported. The probabilistic approach proposed is able to model the deterioration in terms of probability to reach or exceed a given damage threshold $\bar{\ell}$ over time. The assumption of the Log-Normal distributions to model the experimental data has pointed out that the deterioration can change its behaviour over time with an increasing scattering. This behaviour is probably due to the randomness connected with the realisation of the decay process (very similar to the deterioration process that happens in the real environment) and to the characteristic of the specimens (i.e.: presence of mortar joints). Modelling has been made by a computer code involving the maximum likelihood method. Indeed, the modelling of the experimental fragility curves through a Weibull distribution is done by a computer code involving the least square method. In both these cases the values given by the least square method and by the maximum likelihood method and the values of the other statistical test performed, associated to the physical knowledge on the deterioration and on the statistical knowledge, support the choices assumed. In each analysed case the modelling of the experimental fragility curve is satisfactory; nevertheless a small number of samples was used. Therefore, in order to interpret these results much caution is needed. In fact, the number of samples cannot be less than of 4 and the time interval must be long enough. A time test too short gives information that can be modelled only by the inferior tail of distribution. As a consequence, the distribution parameters are evaluated on the base of these data and the fitting can suffer from unreliability. Of course, this depends also on the investigated damage. If the damage to be consider is small (f.i. $\bar{\ell} < 0.2$-0.4%), the time to reach it is short, therefore the time test during which 4-5 measurements are done can be short (4-5 months). If the damage investigated is serious (f.i. $\bar{\ell} > 2.0$-3.0%) the time test must be longer (10-12 months). In this case it will be possible to make prevision of the damage evolution for a long period of time (more than 30 months). In conclusion, the application of this approach is simple, but in order to have significant results the time of monitoring could be very long and the greatest number of data has to be recorded.

QUANTIFICATION OF THE DAMAGE OVER TIME

The results obtained by modelling the experimental data with the procedure presented will be, now, discussed both for single masonry units (Garavaglia *et.al.* 2002*b*) and masonry prisms (Garavaglia *et.al.* 2002c).

Results for Units

The proposed procedure requires a sufficiently representative number of homogeneous specimens and at the moment the available data on single substrates do not allow for the elaboration of the p.d.f., due to the different peculiar condition of each specimen: in fact, only one specimen was used for each type and concentration of salts and for the masonry units only the area loss plotted in percentage over time could be reported. The significant damage threshold $\bar{\ell}$ found for the single units was 0.5%.

Softmud-Brick: after 7 months, the treated single clay units did not show any visible damage for all the three salt concentrations for each of the three types of salt (Fig.9*a,b,c*). The exfoliation is serious in the *untreated* bricks but for the 2.5% and 5% of Na_2SO_4 concentrations and it is starting also 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 worsen the durability of the single materials.

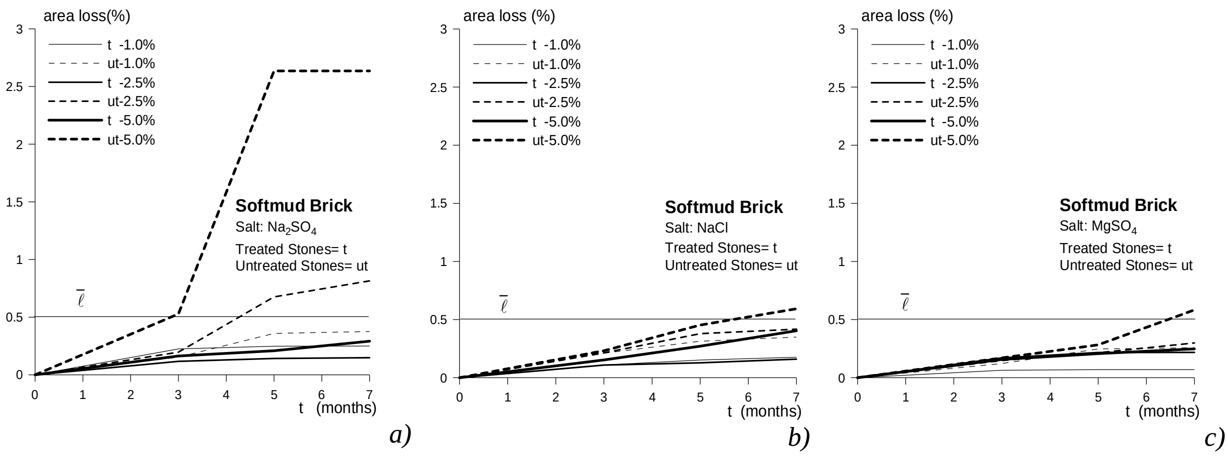
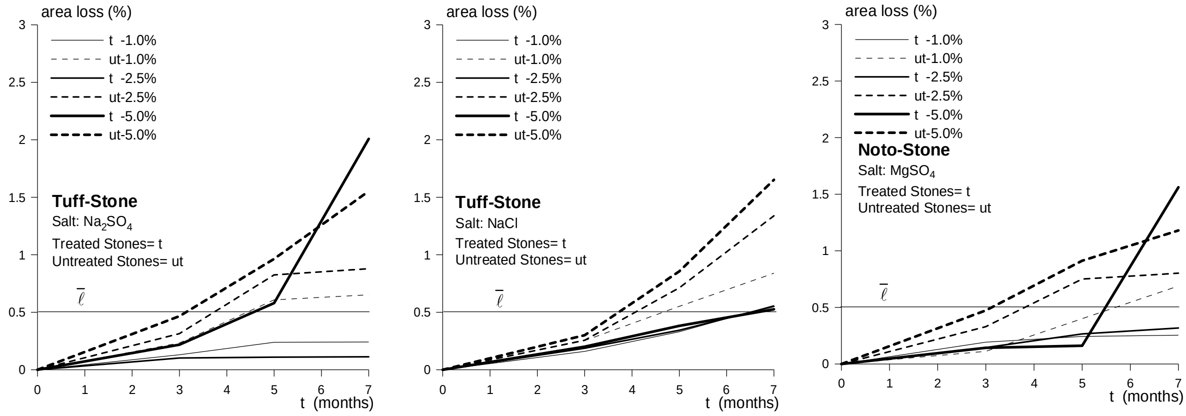


Figure 9. Softmud-Brick: deterioration plots for the three types of salts

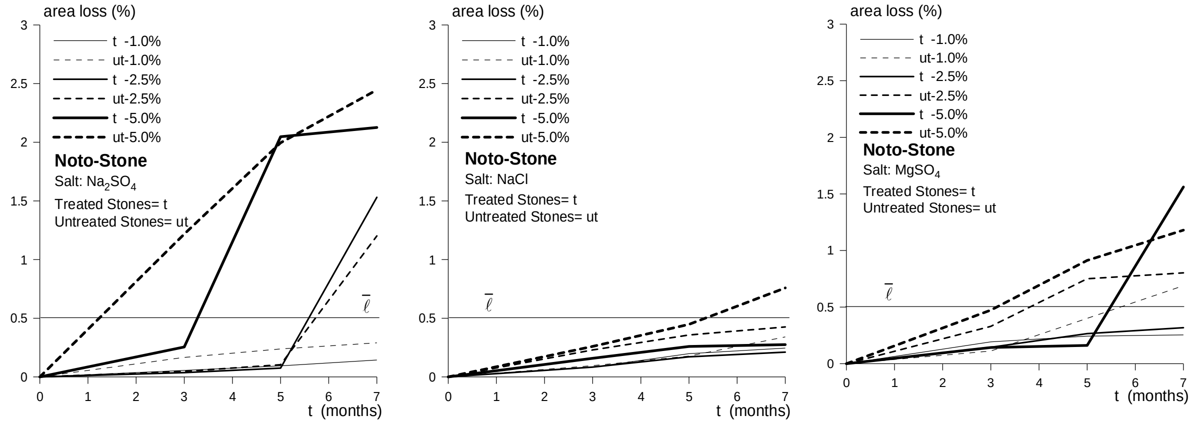
Tuff Stone: this stone, both *treated* and *untreated,* is more sensible to the $MgSO_4$ than to other salts, although the decay is serious also for Na_2SO_4 (Fig.10*a,b,c*). In the case of $MgSO_4$ already after 5 months, the complete detachment of the *treated* layer was observed for the 5% concentration 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 and that means that it is suggested not to treat at all this stone in presence of salts.

Noto Stone: delaminated stone surfaces are visible in many specimens, both *treated* and *untreated* (Fig.11*a,b,c*). Na_2SO_4 with the two higher salt percentages (2.5 and 5%) showed the ineffectiveness of the water based water repellent: a surface layer of about 3 mm detached after 5 months with 5% salt amount and after 7 months with 2.5%. Observing in Fig.11*a* and Fig 12*a*,*b* 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.



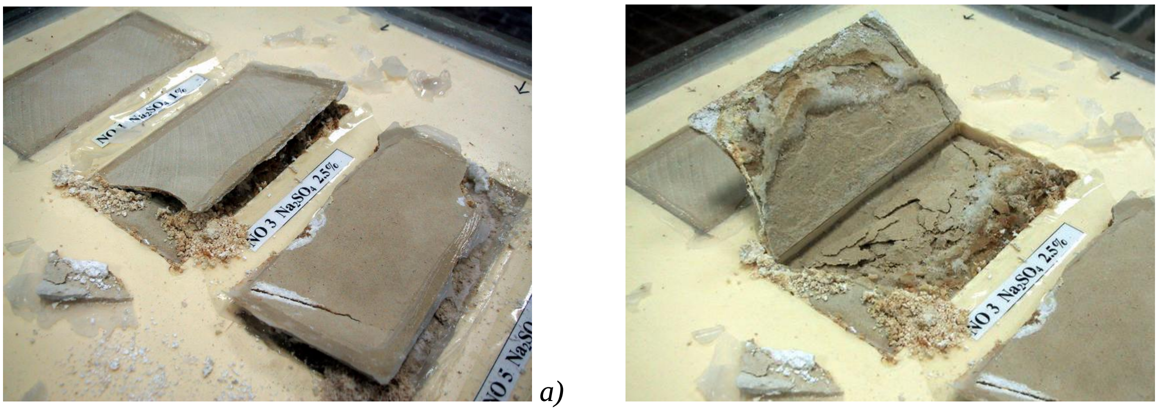
a) *b)* *c)*

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



a) *b)* *c)*

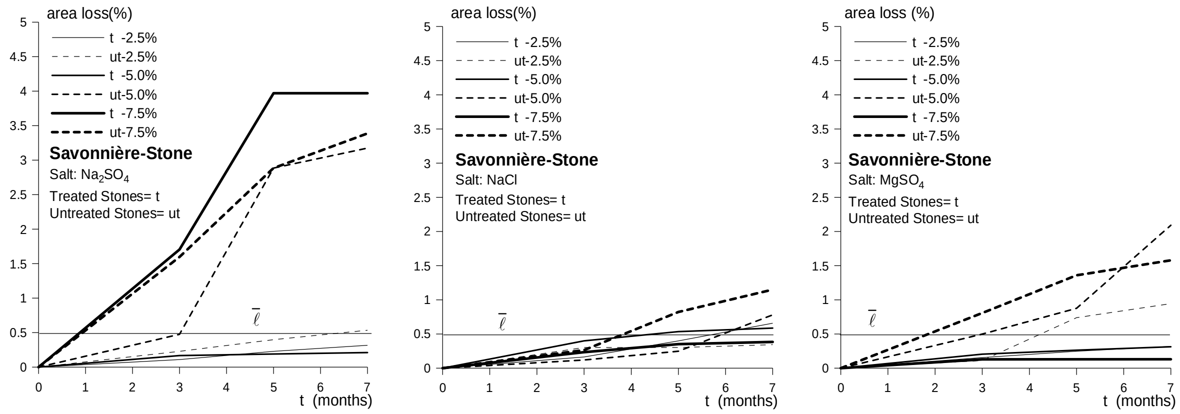
Figure 11. Noto Stone: deterioration plots for the three types of salts



a)
b)

Figure 12a,b. Noto stone units: a) the 3 concentrations of Na_2SO_4 after 7 months; b) the WBWR treatment failed with 2.5% and 5% of salt concentration

Savonnière Stone: in the case of Na_2SO_4 with the highest concentrations (7.5% and 5%) of salts, it is clearly visible from Fig. 13*a* that it is unnecessary to submit the stone to surface treatment. In all the other cases (Fig.13*b*,*c*), the treated specimens behave better than the untreated and seem to tend to an asynthotic value of damage. So in the case of the Savonnière the threshold in concentration could be 2.5%. Sensitiveness is shown also to $MgSO_4$ (Fig. 13*c*).



a) *b)* *c)*

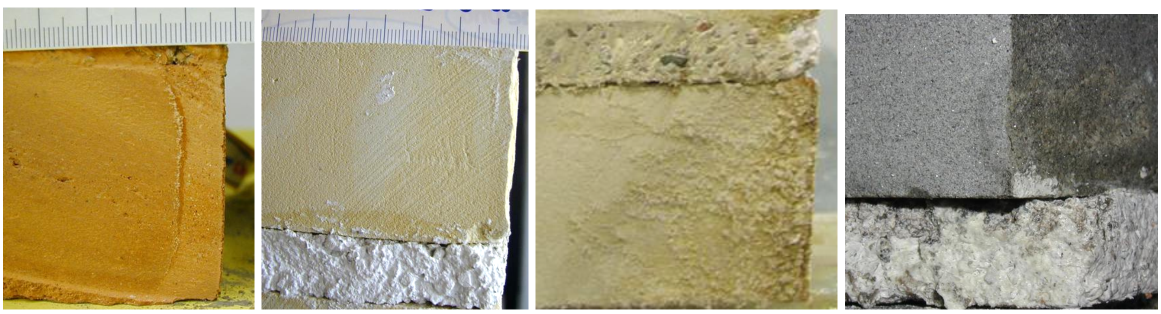
Figure 13. Savonnière Stone: deterioration plots for the three types of salts

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 the full-scale models out door (Binda *et.al.* 1999*b*), it was clear that, even if the stone has low porosity, the decay is accelerated in the walls due to the presence of mortar.

Results for Wallettes

Only the data coming from the wallettes could be reliably used for the elaboration of the probabilistic model, because for each wallette there were at least four units to be measured and therefore a sufficient number of results. The elaboration of the p.d.f. is here described for the units combined with mortar tested with the Na_2SO_4 salt solution. Therefore the fragility curves refer to the stones and bricks in the wallettes. In the case of softmud bricks, the measured decay was similar both for the units with and without mortar joint. In the case of the Noto stones, a visible difference was observed also at the lowest salt concentration (1%). The experimental data elaboration as in Figure 8 was reported in (Cardani *et al.* 2002; Garavaglia *et.al.* 2002c). Due to the still low damage of the Serena and Savonnière stone wallettes only the data on brick and Noto stone wallettes are here presented.

In Figure 14 the presence of salts below the water based water repellent (WBWR) treated layer was evident in all treated wallettes also where the surface damage was still not visible, as for the softmud brick and Savonnière stone wallettes (Figs.14*a* and *c*). The damage in the Serena sandstone wallettes is still localised at the interface mortar/stone (Fig.14*d*).



a) *b)* *c)* *d)*

Figure 14. Presence of salts below the WBWR treated layer: a) softmud brick, b) Noto stone, c) Savonnière stone and d) Serena sandstone

Softmud brick wallettes

The fragility curves of the brick/mortar wallettes with the highest Na_2SO_4 concentration are reported in Fig.15, where a comparison of the two treatments with the untreated reference is made. The consolidant determined soon cryptoefflorescences starting from the interface brick/mortar; after 6 months spalling of layers (corresponding to a level of damage of about 1.2%) it was still continuing (Fig.15*a,b*). On the contrary the water repellent did not produce on the bricks any particular damage within a time of 8 months, therefore the fragility curves could be referred only to a low level of damage. Since the mortar is the only vehicle to water evaporation, the mortar joints are the most damaged, and consequently the decay of the bricks according to the assumed model can be expected within two or three years (Figs.15*a* and 15*d,e*). The damage of the reference untreated wallette for the lowest concentration (1%) was very poor in the first three months, then it started uniformly in the bricks and in the mortar joints. With the highest concentration (2.5 %) the damage became soon serious due to cryptoflorescences for both materials (Fig. 15*c,f*). Comment: as the material loss in untreated wallettes after the same period of time is similar to the ones treated with consolidant, this treatment with this type of bricks seems to be unnecessary to prevent salt crystallisation decay. Up to now no damage is visible on bricks treated with water repellent, but the passed experiences suggest to continue the test.

Noto limestone wallettes

In the short period of 1 month, the stones treated with consolidant, even with the lower salt concentration, presented detachment of a thin layer (about 0,65 mm), corresponding to a level of damage of about 0.8% (Fig.16*a*). After the removal of these layers the stones start powdering uniformly. The mortar showed damage after 3 months but only with the higher concentration.

In the case of water repellent, with the lowest salt concentration of 1% the damage starts slowly and no surface decay is visible on wallettes after the 3 first months. After 6 months the damage due to the presence of water repellent becomes serious showing exfoliation and spalling of stones. With the highest salt concentration of 2.5% the damage is serious from the beginning showing spalling of layers of about 1,4 mm (corresponding to a level of damage of 1.2%). See Fig.16*d,e*. After 6 months the observed damage for both concentration is similar. 1% of Na_2SO_4 could be a threshold but the prevision shows that the probability to reach a serious damage is in two years, as for the reference untreated wallette (Fig.16*c,f*). Noto stone, although it is less porous, shows damage before the softmud brick.

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. The specimens have been subjected to accelerated laboratory tests of salt crystallisation, with 3 different types of salt and different salt concentrations. The proposed modelling procedure, applied in its first part, has been able to evaluate the effectiveness of the surface treatment on the different materials and in the presence of different salts with different concentrations. For the considered time of test, the results have been showing that its efficiency is quite satisfying on fired clay units but not on the analysed natural building stones. In this case the detachment of the treated layer happens in a really short time and the material becomes again untreated. These results however represent the behaviour only of the single units and not their behaviour in the mortar/units system. The approach was also applied to the same units combined with mortar in a wallette. The results showed how this approach is able to predict, in probabilistic terms, the magnitude of the expected damage over time and the occurrence time for a given damage level. Therefore, the use of this approach allows to evaluate the treatment effectiveness on different building materials. The model prediction seems to be confirmed by the real behaviour of the wallettes, also in case where no surface damage was visible. The presence of salts, shown after cutting the specimens at the end of the tests, was evident below the treated layer. This finding leads the authors to the conclusion that the damage will occur anyway. It can at the end be remarked that the success of the application can depend on the type of the studied material combination, on the chosen threshold and that it is important to know deeply the physical aspects of the analysed phenomenon, in order to correctly model it. In order to interpret the results much caution is needed: the number of samples cannot be less than 4 and the time interval between measurements must be long enough to know the behaviour. Of course, this depends also on the investigated damage.

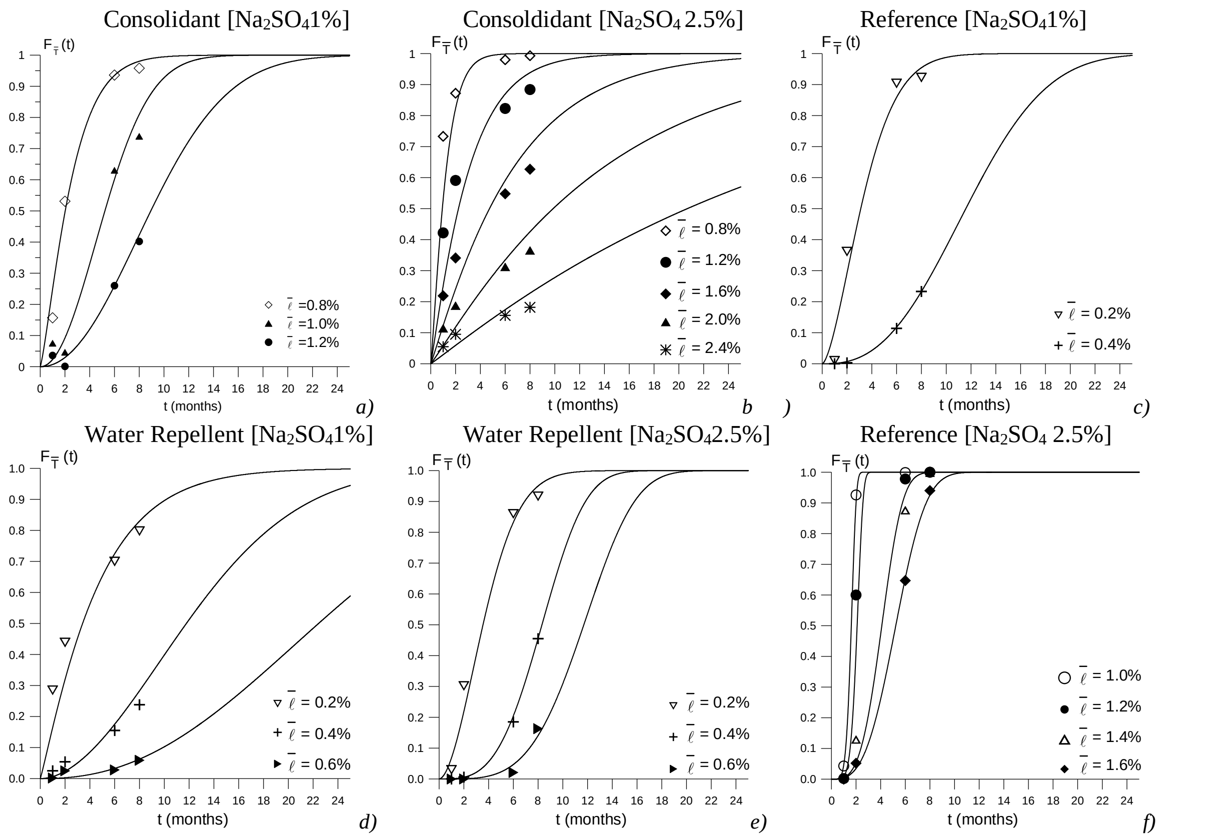


Figure 15 – Fragility curves built on brick/mortar masonry specimens with different surface treatments.

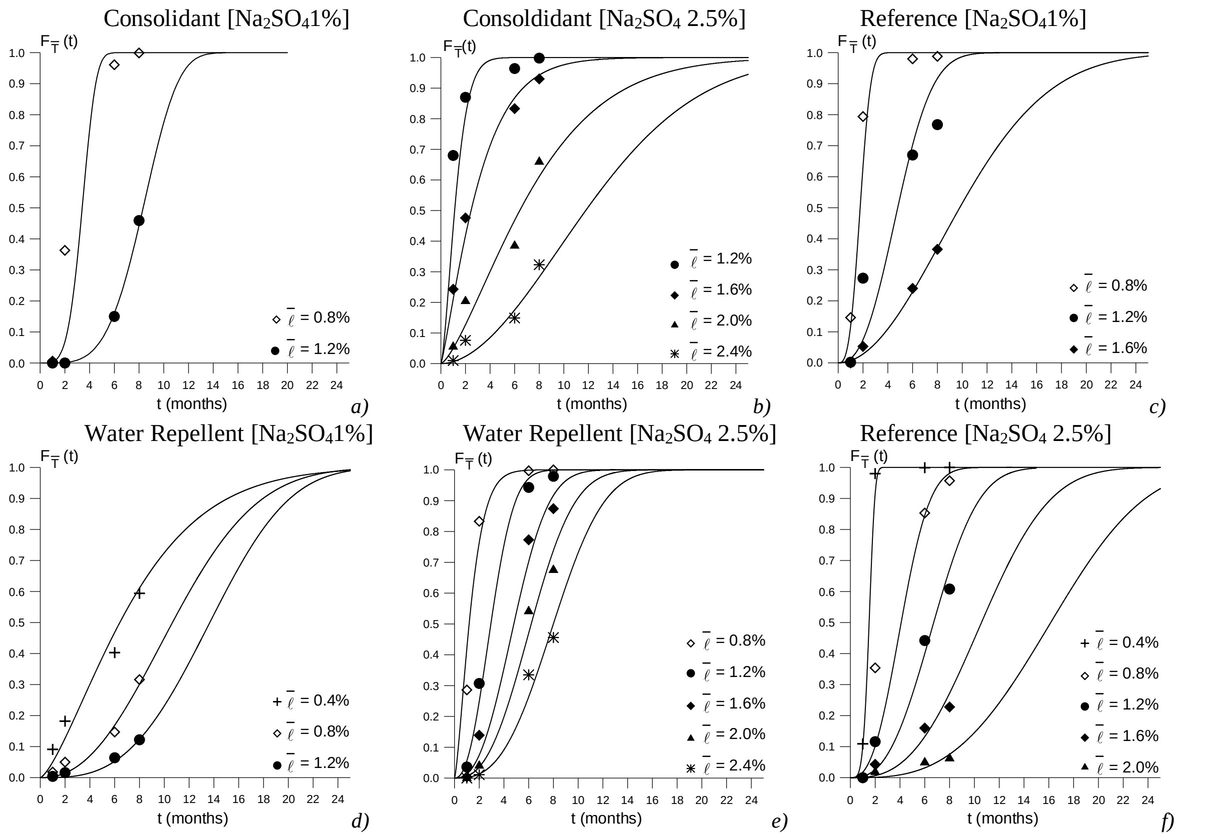


Figure 16. – Fragility curves built on Noto limestone/mortar masonry specimens with different surface treatments.

If the damage to be considered is low ($\bar{\ell}$ < 0.2-0.4%), the time to reach it is short, therefore the time test during which 4-5 measurements are done can be short (4-5 months). If the damage investigated is serious ($\bar{\ell}$ > 2.0-3.0%) the time test must be longer (10-12 months). In this case it will be important to try to use the model to make a prevision of the damage evolution for a long period of time (more than 30 months) without prolonging too much the test duration.

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