Probabilistic model to predict the durability of concrete affected by salt crystallisation.

E. Garavaglia[1] & C. Tedeschi[2]

Abstract. The architectural heritage of the ‘50s, mainly built in reinforced concrete, currently presents serious problems of degradation in the structural members more exposed to environmental aggressiveness. One cause of degradation of the porous materials is the presence of sulphates in the water whose crystallisation causes microfractures inside itself with subsequent detachment of surface layers. It is important to be able to predict the evolutionary trend of such damage on the basis of the composition of the concrete in order to improve its performance. The uncertainties inherent in the phenomenon of degradation suggest a probabilistic approach to this problem. Therefore, to study the decay produced by the presence of sulphates in concrete structures, accelerated durability laboratory tests on concrete specimens were carried out. This decay, quantified in laboratory through a laser-triangulation profilometer, provides the basis on which a probabilistic modelling of the evolution of durability over time was developed.

Keywords: concrete durability, crystallisation tests, laser profilometer, probabilistic model

---

[1] *Politecnico di Milano, Department of Civil and Environmental Engineering, Piazza Leonardo da Vinci 32, 20133 Milan, Italy*
elsa.garavaglia@polimi.it

[2] *Politecnico di Milano, Department of Civil and Environmental Engineering, Piazza Leonardo da Vinci 32, 20133 Milan, Italy*
cristina.tedeschi@polimi.it

Introduction

The '50s and '60s of the last century are to be considered the most fruitful period for the experimental use of reinforced concrete in architecture. In fact, in those years, designers like Le Corbusier, Nervi, Candela, Kahn, Morandi, Musmeci, Ammann, etc. intensified their research on the use of this material in architecture and engineering, thanks to its characteristics that make it unique: a fluidity that allows the construction of interesting plastic shapes and an important strength once it has been put in place and cured.

During its service-life the reinforced concrete shows durability limits, not initially foreseen. Like all porous materials, if immersed in aggressive environments, it suffers from deterioration (Bertolini et al. 1998, Bertolini 2008, Macdonald 2003).

Due to climate change and the high concentration of pollutants in urbanised industrial environment, many buildings and infrastructures in reinforced concrete are undergoing severe deterioration (Brimblecombe 2004). Some of these constructions are of considerable cultural value, because they have marked an era in architecture and, therefore, it is important to preserve them ensuring both the level of performance and the quality of expression.

Many authors have developed research on the decay of reinforced concrete constructions, ranging from identifying the symptoms that lead to deterioration, (Bertolini et al. 1998, Macdonald 2003, Melchers and Li 2009) to the topic of reconversion and reuse of these buildings once they have been restored (Thorne 1997, Allan 2010).

However, the crucial point is to understand how aggressive actions attack the material and how the degradation due to these attacks evolves over time, compromising the performance and the safety of the entire structure. Literature has shown many examples on this subject, too. (Der Kiureghian 2008, Ang 2011, Barone and Frangopol 2014, Sgambi et al. 2014, Garavaglia and Sgambi 2015, Biondini and Frangopol 2016, Garavaglia and Sgambi 2016, Garavaglia, Basso and Sgambi 2018).

The aim of this paper concerns the study of the deterioration of concrete and cement mortars when they are immersed in an aggressive environment and the prediction of the evolution of their degradation over time. As reported in many of the studies cited, (Melcher and Li 2009, Ang, 2011, Garavaglia et al. 2013, Biondini and Frangopol 2016) environmental attacks are assumed as random variables. In fact, occurrence, duration and intensity are usually unknown; even the response of materials under certain stress may show randomness. With regard to building materials (stones, bricks, mortars and cement) the uncertainty of their behaviour towards environmental attacks cannot be neglected, it depends a lot on the inhomogeneity already present in the material itself, e.g. in concrete and mortar the uncertainties are related to the distribution of aggregates, the water/cement ratio, the packaging, the curing and so on. For years the authors have faced the durability of masonry and of its components from a probabilistic point of view (Garavaglia et al. 2008, Garavaglia et al. 2016) as aware of these uncertainties. Thanks to the experience gained and considering the uncertainties previously listed, in this paper it was considered appropriate to address the degradation of concrete over time from a probabilistic point of view.

The probabilistic approach proposed is simple to apply, and efficient, thus allowing:

- to check, at each detection cycle, the loss of performance of a given parameter in relation to the detection point;
- to estimate, in probabilistic terms, the evolution of degradation and, consequently, the time necessary to reach a certain level of damage.

Since it is impossible to take into account all the uncertainties involved in the degradation process and their implications on its evolution, this paper will try to identify a parameter of significant damage (assumed as a random variable of the problem) and study its evolution over time due to a precise induced risk (for example a precise aggressive attack).

To arrive at a correct modelling of the degradation process that affects the concrete immersed in an aggressive environment, research has been carried out to identify one of the most damaging agents for the material. In section 1, sodium sulphate is identified as an important degradation agent for concrete supported by studies of international importance. On the basis of the observations developed in section 1.1, in section 1.2 the reasons for the choice to deal with this problem from a probabilistic point of view are discussed. In section 2 the proposed probabilistic approach is introduced. For a correct application of a probabilistic approach the fundamental base are the data sets and their sample size. The proposed approach can be applied to both existing structures, as long as there is an effective network of damage detection sensors and monitoring time sufficiently long to be reliable from a statistical point of view, and to experimental tests carried out in laboratory in a controlled environment. The data analysed were collected during laboratory tests in a controlled environment. The test procedures developed and the data collected are summarised in section 3. From the results obtained in the laboratory it is possible to identify the loss of surface material as a significant parameter of damage. In Section 4 the detections of the damage at each cycle, the surface roughness through a laser-triangulation CMOS-CCD profilometer is shown. The parameter of damage on which the research will be concentrated is introduced and quantified in section 5, while in section 6 the application of the probabilistic approach in the study of the propagation of damage in the concrete subjected to sulphate attack is introduced. The results obtained are reported in section 6, while the conclusions are reported in section 7.

1. The deterioration of concrete due to environmental attacks

1.1. Sodium Sulphate attacks and its important effects on the concrete durability

Some substances, either occurring naturally or resulting from human activity and found in the soil or in the water, can cause decay in concrete due to chemical reactions that developed with the constituents of the cement matrix. Durability of concrete structures is influenced by sodium sulphate (Na_2SO_4) attack and also by environmental conditions (Alexander, Bertron and De Belie 2013) such as temperature, pH value and sulfate concentration in the salt solution. Sulfate attack is larger in concrete exposed to wet-dry cycling. When water evaporates, sulphate ions can accumulate on the concrete surface, increasing in concentration, thus causing deterioration (ACI Committee 201 1991).

Porous concrete is susceptible to weathering caused by salt crystallisation. Under drying conditions, salt solutions can rise to the surface by capillary action and, as a result of surface evaporation, the solution phase becomes supersaturated and salt crystallisation occurs, sometimes generating pressures large enough to cause cracking and scaling (Scherer 2004).

Sulphate attack on concrete structures has been the subject of several experimental studies, with the damage caused by secondary ettringite formation being predominant at low concentration of sodium sulfate (Akpinar and Casanova 2010, Yu, Sun and Scrivener 2013, Cefis, Comi and Tedeschi 2015), while the damage caused by the formation of gypsum predominates at high concentration of sodium sulfate (Glasser, Marchand and Samson 2008). However, few studies cover the damage of concrete due to crystallization of water soluble sulphate salts with the use of laser scanner to evaluate the damage after wet-dry cycles on concrete blocks (Kim, Hossain and Chi 2011).

1.2. The reasons for a probabilistic approach

One of the problems that cause the deterioration of reinforced concrete structures is therefore the crystallisation of soluble salts present in water and especially sulphates. The damage caused by the crystallisation of these salts is the progressive loss of surface material. This phenomenon depends on many factors that are not always deterministically governable such as: the aggressiveness of the attack, the distribution of the porosity in the material, the distribution of the aggregates, the conglomerate packaging procedure, the laying of concrete and its curing procedure, etc. The life time of the structural elements should also be considered, because it is during this lapse of time that they suffer unknown and often unpredictable a priori attacks.

In such a situation it is inevitable to face the problem from a probabilistic point of view. The research carried out in this field hardly ever deals with the probabilistic problem (Ronziere et al. 2009, Cefis and Comi 2017, Ikumi et al. 2017) indeed, as it is well known, reliable probabilistic analysis requires a significant amount of data and dealing with such a complex issue from surveys on existing buildings involves long and costly monitoring actions.

It is also known that laboratory tests performed following standard recommendations, such as RILEM procedures (RILEM MS-A1 1998), can already provide important information on the evolution of degradation even with the limits imposed by accelerated tests.

The problem of probabilistic modelling of the progressive damage of building materials such as bricks, stones and masonry as a whole has been dealt with since 2000 by the research group led by Luigia Binda (Binda and Baronio 1987, Van Balen et al. 1996, Cardani et al. 2002a, Cardani et al. 2002b). The proposed approach is the interpretation of the problem as a classic reliability problem. This interpretation seems satisfactory and has received international acclaim (Garavaglia, Lubelli and Binda 2002, Garavaglia et al. 2008, Garavaglia et al. 2016).

The degradation of a cementitious material subject to salt crystallisation seems to follow a process very similar to that found in other building materials, therefore it is believed that the probabilistic approach developed by Garavaglia, Lubelli and Binda (2002) can also be effective in modelling of this material.

2. Some notes on the proposed probabilistic approach

The probabilistic approach concerns the construction of fragility curves that are able to describe the probability of reaching and exceeding a certain damage threshold over time. These concepts are explained in the following section.

2.1. Fragility Curves approach

If some significant damage thresholds, $\bar{a}$, are considered and the variable time needed to exceed it must be predicted; then the deterioration process must be treated as a reliability problem where the reliability function $\bar{R}(\tau)$ is the probability that a system exceeds a given significant damage threshold $\bar{a}$ over time τ. The random variable that is used to quantify reliability is $\bar{T}$. $\bar{T}$ is the cycle in which exceeding of the damage $\bar{a}$ can happen with a given level of probability (Garavaglia et al. 2008):

$$\bar{R}(\tau) = \Pr(\bar{T} > \tau) = 1 - F_{\bar{T}}(\tau) \tag{1}$$

where $\bar{R}(\tau)$ is the time dependent reliability function, $F_{\bar{T}}(\tau)$ is the distribution function for $\bar{T}$.

Computing $F_{\bar{T}}(\tau)$for different damage levels $\bar{a}$ allows for the construction of the *fragility curve* for each $\bar{a}$.

A fragility curve describes the probability of reaching or exceeding a given damage $\bar{a}$ over time (or for cycles).

Due to so many uncertainties, we must foresee that, at any time *t**, the level of decay reached from a construction material, affected by an aggressive environment, may be different from point to point of detection and that this variation can be predicted and modelled through an appropriate probability density function $f_a(A)$, (Fig. 1a). The damage modelling, instant by instant, will be the basis for the construction of fragility curves.

In fact, for a chosen damage level $\bar{a}$ at a given cycle τ*, the probability to reach $\bar{a}$ can be seen as the area under the threshold $\bar{a}$ and the probability of exceeding it can be seen as the area over the threshold $\bar{a}$ (Fig. 1a, shaded area).

Indeed, the computed areas over different thresholds $\bar{a}$ provide the experimental exceeding probability used to fit the fragility curves. Therefore, the exceeding probabilities evaluated for each damage level $\bar{a}$ at every cycle τ*, lead to the building of the experimental fragility curves for each chosen $\bar{a}$ and their theoretical modelling $F_{\bar{T}}(\tau)$ (Garavaglia, Lubelli and Binda 2002) (Fig. 1b).

The choice of the density $f_a(A)$ for the modelling of the damage level, instant by instant, is very delicate, as is the choice of the probability distribution $F_{\bar{T}}(\tau)$ for the theoretical interpretation of the experimental distribution of the exceedance probability for every threshold.

Here Fig 1

Fig. 1 Probability to cross the threshold $\bar{a}$: a) Log-Normal p.d.f. modelling damage at each t*; b) experimental (▲) and Weibull theoretical (—) fragility curves

This choice cannot overlook the correct physical knowledge of the phenomenon studied and the knowledge of the behaviour of the distributions in their tails, a behaviour governed by the failure rate function:

$$h_{\bar{T}}(\tau) = \frac{f_{\bar{T}}(\tau)}{1 - F_{\bar{T}}(\tau)} \qquad (2)$$

where $h_{\bar{T}}(\tau)$ is the time dependent failure rate function, $f_{\bar{T}}(\tau)$ is the probability density function of the variable $\bar{T}$ and $1 - F_{\bar{T}}(\tau) = \Im_{\bar{T}}(\tau)$ is the survivor function of $\bar{T}$.

As explained in (Garavaglia, Lubelli and Binda 2002) each behaviour assumed by (2) is characteristic of a certain type of distributions, this is the reason why it has been stated that the choice of the distribution for a probabilistic modelling of a given phenomenon cannot disregard the knowledge of the physical behaviour of the phenomenon.

On the basis of these observations, it will be possible to proceed with the choice of the most suitable distribution.

3. Laboratory tests development

3.1. Specimens details

The experimental study of the surface deterioration of the cement aggregate subjected to salt crystallisation of dissolved sulphates was designed following the RILEM procedure (RILEM MS-A1 1998), and carried out on the series of samples suitably packaged.

The specimens of concrete (150mm x 150mm x150mm) were cast in two different days characterized by different humidity conditions and in series of eight cubes. The acronyms 1R and 2R identify the specimens produced in the two different days. The specimens' preparation was the same for both the days; it consisted in a concrete mix design prepared with 0,45 water to cement ratio, 250 Kg/m^3 cement content (CEM II / A-LL 42.5 R, chemical composition reported in Table 1) and 32mm maximum siliceous aggregate size.

The concrete cubes carried out were cured in a controlled environment laboratory at 20°C and 90% RH for 28 days.

Here Tab. 1

Table 1 Chemical composition of the cement

After curing, the specimens were subjected to durability tests according to RILEM MS A.1 (1998). They were filled with a 10% of Na_2SO_4 solution concentration for 24 hours to develop the accelerated ageing of the specimens due to crystallization phenomena. Then they were stored on a layer of a dry gravel into a plexiglas box open at the top, with the upper surface exposure to 20°C and 50% RH (Fig.2a). At 4 week intervals (4 weeks corresponding to one cycle), the specimens were subject to: a) visual inspection, b) photographic survey, c) description of the efflorescence, d) cleaning the surface of efflorescence and detached material with a soft brush, e) photographic survey, f) description of the damage, g) monitored the surface area with a laser profilometer to evaluate the damage. To restart the natural crystallization phenomena and the process of decay demineralized water was added every 4 weeks resulting in the beginning of a new cycle.

Here Fig. 2

Fig. 2 a) Scheme of the specimen for crystallization test; b) scheme the profile measurements of the specimens 1R8 and 2R7 assumed for probabilistic analysis (red areas)

The measurements recorded at each 4-week cycle using the laser profilometer, showed a modified surface because of the decay due to the loss of material. This type of damage can be quantified calculating the area included between two contiguous profiles. These results were then used to define a probabilistic model.

On the basis of the results obtained by the durability tests, to approach the probabilistic interpretation of the data recorded only two specimens were chosen: 1R8 and 2R7 which could be considered representative of the entire sample size.

3.2. Some consideration after the durability tests and the visual observation

By visual observation it seems that at the end of the crystallization test (month T_{24}, 24 months, after its beginning) the specimen 1R8 seems to be more damaged than the specimen 2R7. The decay of the specimen 1R8 develops on all surfaces exposed to the aggressive environmental conditions. The specimen 2R7 is damaged along the edges and in a limited area, from the top of the concrete casting to about 35mm of depth (Fig. 3).

Here Fig. 3

Fig. 3 Surface slice of the specimens 1R8 e 2R7 after 24 month cycles.

The decay recorded on the cubes is probably influenced by the porosity of the material and by the pore distribution. Each specimen is characterized by a distribution of aggregates and by the pore characteristics that change for each specimen even if the specimens were cast using the same mix design. The characteristics just described, influence the capillary rise and the salts crystallization in the material. On this topic new research are in progress with the aim to catch a relation between pore distribution, size and decay velocity.

3.3. Damage measurement by laser profilometer

The superficial damage suffered by the material in each crystallisation cycle is estimated through the relief of surface roughness variations. This operation is performed with a laser profilometer (Fig. 4a). Over the years there has been an evolution in the equipment to detect the roughness of the surface, this equipment has gone from a linear reading (Cardani et al. 2002a and 2002b, Binda, Cardani and Tedeschi 2005) to a reading of the area (Fig.4b) (Tedeschi et al. 2010).

The profilometer used in this study is a laser- Triangulation CMOS-CCD profilometer (Fig. 4a). The profilometer had a biaxial system (X, Y) with linear axis controlled by servomotors, high precision movement (positioning, repeatability and guiding) with a maximum dimensions of the axis of 600mm x 600mm. It is an optoelectronic displacement measurement system with an integrated digital signal processor. This sensor measures position against almost any target without touching the specimen by means of a triangulation arrangement (measure range: 50mm; linearity: ±0.2%; resolution static: 5µm and dynamic: 25µm; measuring rate: 1KHz).

The laser profilometer allows quantifying the loss of material on the exposed surface, by comparing the measurements from the start (T_0) to the end of the cycles (T_{18}) with a 0.5mm resolution.

Profiles recorded at the end of each salt crystallization cycle showed the changes of the surface over time due to the progress of decay. Therefore, the loss of material was measured starting from the second month from the beginning of the test (Garavaglia, Lubelli and Binda 2002).

Since each consequent profile was the measure of the loss of material during the previous cycle (4 weeks), the damage can be assumed as the loss of material itself and quantified as the area included between two contiguous profiles (an example is the dashed area in Fig. 5). These results can be used for probabilistic modeling of the progressing damage (Garavaglia et al. 2008) and for the life cycle assessment of the concrete specimens produced in different period and subjected to salt crystallization.

Here Fig.4

Fig. 4. a) Laser profilometer; b) Profilometer cycle by cycle surface reading

Here Fig. 5

Fig. 5 Example of the area included between two contiguous profiles recorded with the profilometer.

4. Probabilistic modeling of surface deterioration

4.1. The choice of the suitable damage parameter

The loss of material assumed to quantify the damage of concrete decay due to salt crystallization was measured as the area between two contiguous profiles recorded cycle by cycle. Therefore, for each profile i, the loss a_i was computed at every cycle. To compare the results obtained, the damage was plotted in percentage:

$$a_i(k) = \frac{A_i(k)}{A_T} \qquad (3)$$

where $A_i(k)$ (lost area) is the area included between two consequent profiles in position k (Fig. 5, dashed area) recorded at the t_i and A_T is the transversal section area (rectangular gray area in Fig. 2). A simple linear interpolation of the experimental data provided a quite readable trend of the behavior of the loss $a(k)$ over time where $a(k)$ (Eq. 4) is assumed to be the sum of the area lost till the instant t^* by profile in position k (Fig. 6a)

$$a\ (k) = \sum_{i=1}^{n} a_i(k) \qquad (4)$$

Here Fig. 6

Fig. 6. a). Loss vs. time: example of behavior; b) Example of log-normal distribution of loss of material vs. time

4.2. The modelling

During the laboratory tests, the measurements can be made following a precise program (i.e. weekly or monthly cycles), and referred to a time variable τ. As expected, the measurements made at the same time on different profiles showed dispersion around the average value. Therefore, at each instant τ, the deterioration process was assumed only as function of the random variable a. To model this behavior, the choice of an adequate distribution function is needed. This choice is not simple: it must be based on the knowledge of the modeled physical phenomenon and of the mathematical frame governing the behavior of tails distribution.

The physical model suggests that the loss of surface material for salt crystallization can be classified into a given interval of size.

The immediate loss larger than that usually recorded is an extremely rare event, and again the larger the loss expected the smaller the probability that it could happen in the analyzed cycle.

On the basis of the experimental evidence, the probability density function (p.d.f.) chosen to model the material loss is the Log-Normal p.d.f. having the following mathematical form:

$$f_a(A) = \frac{1}{A\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln A - \mu)^2}{2\sigma^2}\right] \qquad (5)$$

where μ and σ are the mean and the standard deviation of distribution and A is the random variable describing the area lost.

The immediate failure rate function, $h_a(A)$, of Log Normal distribution is a function that decreases when the loss value *A* increases, so it seems good to interpret the behavior of the loss at each cycle (Fig. 6b) (Garavaglia, Lubelli and Binda 2002).

The next step has been the building of the fragility curves $F_{\bar{T}}(\tau)$. To model numerically the experimental fragility curves a function has also to be chosen that should provide a good interpretation of the physical phenomenon: in all the damage cases studied here, a Weibull distribution has been chosen (Garavaglia, Lubelli and Binda 2002):

$$F_{\bar{T}}(\tau) = 1 - \exp[-(\rho\tau)^{\alpha}] \qquad (6)$$

with $\alpha > 0$ indicating the shape parameter of the distribution and $\rho = \Gamma(1 + \frac{1}{\alpha})/\mu > 0$, where μ is the mean value of the distribution and Γ is the Eulero's Gamma function, indicating the scale parameter of the Weibull.

Of course, the choice has been based on a physical interpretation of the decay process induced in the porous building materials by environmental aggressive agents over time.

The decay process can be interpreted like a dynamic process that, being the material under attack, constantly evolves describing how its performance can be compromised.

If some significant damage levels, *a,* are defined, the decay process shows how the material reaches and exceeds each of them over time. If the cause of damage endures, the damage advances and, therefore, if a given damage level $\bar{a}$ has not yet been reached at the time *t,* the probability that it can happen in the next immediate interval $d\tau$ increases; hence, the probability increases if τ tends to infinity.

The behavior here described seems to be well modelled by a distribution having an increasing hazard rate $h_{\bar{T}}(\tau)$. Weibull distributions present exactly this type of failure rate.

5. Application of the probabilistic modelling to the case study

In this section the results obtained on 1R8 and 2R7 specimens from T_0 to T_{18} cycles are discussed.

5.1. 1R8_Specimen

The deterioration process of the specimen 1R8 was analyzed along the two strips: one damaged and one undamaged; each strips consisting of 40 profiles.

5.1.1. 1R8_D damaged strip

Profile measurements show how the lack of homogeneity of the conglomerate affects the damage. By profilometer records and visual inspection it seems evident that the behavior of profiles of the damaged strip is characterized by an important swelling. It starts from the twelfth month and it causes the detachment of some material up to the seventeenth month. Probably the detachment is due to expulsion of one aggregate with the consequent formation of a gap/isolated depression.

Figure 7a shows the probability density of recorded material loss month by month. Note that for the 9th and 10th month they are characterised by a slightly higher dispersion, a symptom that in some points the loss of material is higher than other points of the strip. The highest modal value is recorded for profile 12, this is also a symptom of possible swelling and loss of material. The behaviour then remains constant up to 18 months when the dispersion returns to be similar to that of the first months, a sign that the separation has now taken place. The results shown in Figure 7 seem to confirm the deterioration observed during the visual inspections performed.

In Figure 7b the modelling $f_a(A)$ of the progressive loss $a(k)$. In Figure 7b the 4 damage thresholds which are considered to be significant in the accelerated laboratory test are also reported. The four chosen thresholds: $\bar{a}$=0.05; $\bar{a}$=0.10; $\bar{a}$=0.15 $\bar{a}$=0.20, will be used in all the elaborations performed for the construction of the fragility curves following the procedure presented in Section 2.1.

Here Fig. 7

Fig.7, 1R8_D damaged strip (in red) Log-Normal probabilistic density modeling $f_a(A)$ of the damage over time.

5.1.2. 1R8_ND Undamaged strips

The behavior during the cycles for undamaged strips is different. The decay is widespread and there is a progressive swelling as from the twelfth month, but no detachment occurs until T_{18}. In some profiles a strong decrease is present and it’s related to the presence of holes on the surface due to the concrete withdrawal or its packaging.

From T_7 onwards then there is a loss of material in correspondence of all profiles of the strip, but no swelling was visible before. This behavior is shown in Fig 8a, which summarizes the probabilistic modeling of these phenomena. In Figure 8b the modelling $f_a(A)$ of the progressive loss $a(k)$ is reported. In this case the progressive loss shows a greater dispersion in the measured loss values but the tendency to damage progression (Fig. 8b) is very similar to the trend shown by the strip 1R8_D (Fig.7b). The reason for this behaviour in the apparently undamaged strip may be due to the presence of the surface voids.

Here Fig. 8

Fig. 8 1R8_ND Undamaged strip (in red) Log-Normal probabilistic density modeling $f_a(A)$ of the damage a) cycle by cycle; b) over time.

Following the procedure proposed in Section 2.1 and 4.2, the fragility curves were built for both strips 1R8_D (damaged strip) (Fig. 9a) and 1R8_ND (undamaged strip) (Fig. 9b).

Here Fig. 9

Fig. 9 Weibull distribution modelling the fragility curves: a) 1R8_D; b) 1R8_ND

Even the fragility curves do not seem to report differences in behaviour. The results reported in Table 2 for a probability of exceeding the thresholds $\bar{a}$, equal to 20%, show a slightly faster deterioration rate for the undamaged strip, a trend that is reversed in probability of occurrence above a certain percentage (i.e. 60% in Table 2).

Here Table 2

Table 2 Prediction instant of crossing $\overline{a}$ with probability of occurrence equal to 20% and 60%.

5.2. 2R7 Specimen

The decay on the specimen 2R7 were analysed along two strips in two different positions and also in this case the damage seems to be different according to the position of the two strips analysed. The results of the profilometer reading are listed in the following.

5.2.1. 2R7_D damaged strip

Inhomogeneity of the material influences decay. Cycle after cycle the surface of this specimen indicated most damage and it presents always greater roughness. From T_0 to T_8 there is a progressive decay with swelling, even limited swelling, that caused the detachment of material or the loss of aggregates and the formation of depressions in the specimen.

The high variation of deterioration along the whole strip is evident by the large dispersion present in distributions modelling the damage, cycle by cycle (Fig. 10a) and of the density $f_a(A)$ of the progressive loss $a(k)$ throughout the duration of the test (Fig. 10b).

Here Fig. 10

Fig. 10 2R7_D Log-Normal probabilistic density modeling $f_a(A)$ of the damage a) cycle by cycle; b) over time.

5.2.2. 2R7_ND Undamaged strip

The decay of the 2R7 specimen is equal and very low for each profile analyzed for the undamaged area.

This result is confirmed by the probabilistic modelling of the damage. In Figure 11 the probability distribution shows a very narrow distribution, which represents a low dispersions of the data collected.

Here Fig. 11

Fig. 11 2R7_ND Log-Normal probabilistic density modeling $f_a(A)$ of the damage a) cycle by cycle; b) over time.

Figure 12 shows the fragility curves plotted for the specimens 2R7_D and 2R7_ND and for the thresholds $\bar{a}$=0.05; $\bar{a}$=0.10; $\bar{a}$=0.15 $\bar{a}$=0.20

Here Fig. 12

Fig. 12 Weibull distribution modelling the fragility curves: a) 2R7_D; b) 2R7_ND

Also the fragility curves in Figure 12 and the probability of occurrence reported in Table 3 showed the difference in behaviour between the 2R7_D and 2R7_ND strips. The strip 2R7_D showed a behaviour very similar to the 1R8 specimen while confirming what was detected at the end of the test, i.e. that the 1R8 specimen at the end of the test showed a degradation higher than that detected in the 2R7 specimen. On the other hand, the 2R7_ND strip showed a distinctly different behaviour: the probability of occurrence of losses is very much shifted over time (Tab. 3) so much so that for the last threshold it was not possible to predict the probable time of occurrence. The behaviour of this strip is found on most of the surface of the 2R7 specimen excluding the edge strips.

Here tab. 3

Table 3 Prediction instant of crossing $\overline{a}$ with probability of occurrence equal to 20% and 60%.

The different behavior of the two samples analyzed may be due to the different environmental conditions of the site where the samples were prepared. These conditions may have caused a change in the porosity of the concrete and the consequent different damage, even if the mixture, the formwork and the packaging procedure were the same for all the samples.

Conclusions

Because of the many uncertainties in the realization of aggressive environmental attacks, in their magnitude and duration, it seems to be useful to face the problem of the degradation of building materials immersed in such environments using probabilistic approaches.

As is well known, such approaches, in order to be considered reliable, require suitable sample sets collected over a sufficiently long time interval. Getting on-site sampling that meets these needs is not simple, but, thanks to accelerated tests performed in the laboratory following appropriate recommendations (RILEM MS-A1 1998) it is possible to obtain a simulation of the behaviour of these materials in an aggressive environment and a sufficiently reliable sampling of data.

The probabilistic model proposed in this paper, although having an applicative value to real cases monitored over a sufficiently long period of time, is presented here and applied to data recorded in the laboratory with accelerated tests. Thanks to the use of a 2D Laser profilometer, it has been possible to base the analyses on a rather large data-set (readings every 5mm in the X and Y directions, on a surface of 22500mm^2). The aim of the research was to understand and predict the evolution of the deterioration of the concrete subjected to the attack of sulphates, one of the most aggressive agents for this type of material.

Preliminary results obtained through crystallization tests on concrete specimen put in evidence the variability of the specimen used with the same mix design. Probably the different behavior is connected with the different pore distribution and the thickness of the specimens that influenced the capillary rise and the salts crystallization in the material. The loss of material caused by swelling and detachment of cement paste or small aggregate in the specimen 1R8 is widespread on all surface, while in the specimen 2R7 it is concentrated along the borders.

The application of the proposed probabilistic approach, based on the building of the fragility curves, allowed to model, in probabilistic terms, both the degradation of the concrete at each cycle and its evolution over time. The visually identified behaviour was confirmed by these models: the sample 1R8 and the strip 2R7_D showing a higher porosity have a very similar behaviour in the quantification of the loss of surface material at each cycle and in its progression over time, in fact, the pdf of the figures 8, 10 and 13 are very similar: a behaviour similar to the behaviour shown by the strip 2R7_D was also detected on the edges of the specimen, while the remaining portion of the surface shows a behaviour similar to that recorded for the strip 2R7_ND (Fig. 11).

The construction of the fragility curves has allowed to estimate, in probabilistic terms, the times of occurrence of a given level of damage. Their structure is flexible and able to capture different behaviours due to the randomness that affect the environmental attacks, the packaging and curing of the concrete, and the composition of the material itself. The fragility curves have shown even more clearly the importance of a certain care in the packaging of the material and this because the initial superficial roughness and presence of voids and small cavities facilitate the degradation due to salt crystallisation.

The authors believe that the proposed approach is easy to apply since it can be performed using commercial statistical codes, but has an interesting predictive value on the evolution of degradation in construction materials.

A future development of this research will be to test the reliability of the method with a lower number of data hoping to be able to establish the minimum number of detection moments (or laboratory cycles) for a reliable life cycle forecast of a building material.

References

ACI Committee 201. (1991). "Guide to durable concrete". *ACI Mater J.*, 88 (1991), 54-82.

Akpinar P., and Casanova I., (2010). "A combined study of expansive and tensile strength evolution of mortars under sulfate attack: implications on durability assessment". *Materiales de Construcción,* 60 (297), 59-68.

Alexander, M., Bertron, A., and De Belie N. (Eds.) (2013). „*Performance of Cement-Based Materials in Aggressive Aqueous Environments".* Springer. Ed., RILEM State-of-the-Art-Report. Berlin.

Allan, J. (2010). "Private privilege - public duty: examples of recent English experience in modern conservation". *J. of Arch.,* 15 (5), 651-70.

Ang, A. H. -S. (2011). "Life-cycle considerations in risk-informed decisions for design of civil infrastructures". *Struct. Infrastruct. Eng.*, 7(1–2), 3-9.

Barone, G., and Frangopol, D. M. (2014). "Reliability, risk and lifetime distributions as performance indicators for life-cycle maintenance of deteriorating structures". *Reliab. Eng. Syst. Saf.*, 123, 21-37.

Bertolini L., (2008). "Steel corrosion and service life of reinforced concrete structures". *Str. and Infrastr. Eng.*, 4(2), 123-137.

Bertolini L., Bolzoni F., Pedeferri P., Lazzari L., and Pastore T., (1998). “Cathodic protection and cathodic prevention in concrete: principles and applications”. *J. App. Electroch.*, 28(12), 1321-1331.

Binda L, Cardani G., and Tedeschi C. (2005). “The evaluation of damage due to salt crystallisation of different re-pointing mortars studied in laboratory”. *10th Int. Conf. on Durability of Building Materials and Components* (10DBMC), (CD-ROM), Lyon, France, 17-10/4/2005.

Binda L., and Baronio G. (1987) “Salt decay of masonry structures: an approach to service life design: experimental research”. Interim Report, 1st USA-ITALY. *Ws on Evaluation and Retrofit of Masonry Structures*, Milan, 24-32.

Binda, L., and Molina, C. (1990). “Building Materials Durability Semi-Markov Approach”. *J. Mat. Civ. Eng.*, 10.1061/(ASCE)0899-1561(1990)2:4(223).

Biondini F. and Frangopol D.M. (2016). “Life-Cycle Performance of Deteriorating Structural Systems under Uncertainty: Review”. *J. of Str. Eng.,* 10.1061/(ASCE)ST.1943-541X.0001544.

Brimblecombe P. (2004). “Damage to Cultural Heritage”. *Inter. Workshop on Air Pollution and Cultural Heritage*, December, 1-3, 2003, Sevilla, Spain, Saiz-Jemenez C. Editor, Taylor & Francis Group, London, 88-96.

Cardani G., Tedeschi, C., Binda L., and Baronio G. (2002a) “Crystallisation Test on Treated Brick/Stone Masonry. Specimens for Damage Evaluation”. *Int. Conf. 9th Durability of Building Materials*, (CD-ROM), March, 17-20, 2002, Brisbane, (Australia).

Cardani G., Tedeschi C., Binda L., and Baronio G. (2002b) “Laboratory investigation on the durability of joint re-pointing in brick masonry damaged by salt crystallization”. *6th Int. Masonry Conf.*, Nov., 4-6, 2002, London, N.9, 65-72.

Cefis N. and Comi C. (2017). “Chemo-mechanical modelling of the external sulfate attack in concrete”. *Cem. Conc. Res.*, 93(3), 57-70.

Cefis N., Comi C., and Tedeschi C. (2015). “Modellazione del degrado nel calcestruzzo dovuto a formazione di ettringite secondaria”. *XII Con. Ass. It. di Meccanica Teorica e Applicata*. Genova, Italy, Sept., 14-17, 2015, 488-497 (in Italian).

Der Kiureghian, A. (2008). “Analysis of structural reliability under parameter uncertainties”. *Probab. Eng. Mech.*, 23(4), 351–358.

Garavaglia E., and Sgambi L. (2016). “Selective maintenance planning of steel truss bridge based on the Markovian approach”. *Eng. Str.*, 125 (15 October 2016), 532-545.

Garavaglia E., Anzani A., Binda L. and Cardani G. (2008). “Fragility curve probabilistic model applied to durability and long term mechanical damages of masonry”. *Mat. Str.*, 41(4), 733-749.

Garavaglia E., Basso N., and Sgambi L. (2018). “Probabilistic life-cycle assessment and rehabilitation strategies for deteriorating structures: a case study”. *Int. J. Arch. Heritage*, 12 (6), 981-996.

Garavaglia E., Lubelli B. and Binda L., (2002). “Two Different Stochastic Approaches Modelling the Deterioration Process of Masonry Wall over Time”. *Mat. and Str.*, 35(4), 246-256.

Garavaglia E., Pizzigoni A., Sgambi L., and Basso N. (2013) “Collapse behaviour in reciprocal frame structures”. *Str. Eng. Mech.*, 46(4), 533-547.

Garavaglia E., Tedeschi C., Perego S, and Valluzzi M. R., (2016). “Probabilistic Modelling of the damage induced by salt crystallization in fiber reinforced clay brick masonry”. *IB2MAC, 16th Int. Brick and Block Masonry Conf., Trends, Innovations and Challenges*, (CD-ROM), Padua, Italy, June, 26-30, 2016, C. Modena, F. da Porto & M.R. Valluzzi Editors, CRC Press, Taylor & Francis Group, London, UK, 487-494.

Garavaglia, E. and Sgambi L. (2015). “The use of a credibility index in the life-cycle assessment of structures”. *Str. Infrastr. Eng.*, 11(5), 683-694.

Glasser F.P., Marchand J. and Samson E. (2008) “Durability of concrete – Degradation phenomena involving detrimental chemical reactions”. *Cem. Conc. Res*. 38(2) 226-246.

Ikumi T., Cavalaro S. H.P., Segura I., de la Fuente A. and Aguado A. (2017). “Simplified methodology to evaluate the external sulfate attack in concrete structures”. *Mat. Des.*, 89 (2017).

Kim Y.J., Hossain M. and Chi Y. (2011). “Characteristics of CFRP-concrete interface subjected to cold region environments including three-dimensional topography” *Cold Reg. Sc. Tech.,* 67 (2011), 37-48.

Macdonald S. (2003). “*Concrete Building Pathology”*, Blackwell Science Ltd, Oxford, UK.

Melchers R. E., and Li, C. Q. (2009). “Reinforcement corrosion initiation and activation times in concrete structures exposed to severe marine environments”. *Cem. Concr. Res.,* 39(11), 1068–1076.

RILEM MS-A.1 (1998) “Determination of the resistance of wallets against sulphates and chlorides”. RILEM TC 127-MS: Test for masonry materials and structures. *Mat. Str*., 31(Jan.-Feb. 1998), 2-19.

Roziere E., Loukili A., El Hachem R., and Grondin F. (2009). “Durability of concrete exposed to leaching and external sulphate attacks”. *Cem. Conc. Res.* 39(12), 1188-1198.

Scherer G. W. (2004). “Stress from crystallization of salt”. *Cem. Conc. Res.* 34(9), 1613-1624.

Sgambi L., Garavaglia E., Basso N., and Bontempi F. (2014). “Monte Carlo simulation for seismic analysis of a long span suspension bridge”. *Eng. Str.*, 78 (2014), 100 – 111.

Tedeschi C., Binda L., Gulotta D. and Toniolo L. (2010). “Durability to salt decay of commercial ready-mixed mortars for the conservation of cultural heritage”. *2nd Conf. on Hist. Mortars - HMC 2010 and RILEM TC 203-RHM final workshop,* J. Valek, C. Groot, J.J. Hughes (eds.), Rilem Publication SARL, 2010, 1015-1022, Prague, Czech Republic.

Van Balen K., Binda L., van Hees R.P.J., and Franke L. (1996). “Damage to historic brick masonry structures masonry damage diagnostic system and damage atlas for evaluation of deterioration”. *8th Int. Congr. on Det. and Conser. of Stone*, Berlin, Vol. 3, 1687-1693.

Yu C., Sun W., and Scrivener K., (2013). “Mechanism of expansion of mortars immersed in sodium sulfate solutions”. *Cem. Conc. Res.*, 43(1), 105-111.

APPENDIX I NOTATION

The following symbols are used in this paper

a = loss of material

$a\ (k)$ = sum of the area lost till the instant t^* by profile in position k

$a_i\ (k)$ = percentage of area lost on profile i in position k

$\bar{a}$ = significant damage threshold

$A_i\ (k)$ = area lost between two consequent profiles in position k during the cycle i

A_T = transversal section area

D = damaged strip

exp = 2.718281828

f_a = probability density function of a

$f_{\bar{T}}$ = probability density function of $\bar{T}$

$F_{\bar{T}}$ = cumulative distribution function of $\bar{T}$

$\Im_{\bar{T}}$ = survivor function of $\bar{T}$

$h_{\bar{T}}$ = failure rate function of $\bar{T}$

ND= undamaged strip

$\bar{R}$= probability to exceed the threshold $\bar{a}$

T_{number} = month of reference

$\bar{T}$ = time to exceed $\bar{a}$

t^* = time instant

α; ρ = shape and scale parameters of Weibull distributions

μ;σ = parameters of Lognormal distributions

τ^* = time of experimental measure (cycle)

τ= time

Table and Figure Captions

Table 1 Chemical composition of the cement

Table 2 Prediction instant of crossing $\overline{a}$ with probability of occurrence equal to 20% and 60%.

Table 3 Prediction instant of crossing $\overline{a}$ with probability of occurrence equal to 20% and 60%.