3
Deterioration processes in reinforced concrete: an overview

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Abstract: The various mechanical and physicochemical processes that induce the degradation of the material condition of reinforced concrete (RC) structures are described. Such degradation endangers the structural safety and increases the costs of maintenance and repair. Thus, for safety and economic reasons, it is important to correctly assess the condition of RC structures. The causes and mechanisms of the most common processes of deterioration are summarized, the pathologies and influential factors are identified and details given on how information about damaged structures can be collected. The useful information required for assessment is divided into three series of data: those related to the actual material condition, those related to the evolution of damage, and environmental factors. The weight of the latter is further discussed, since the influence of environmental factors on deterioration mechanisms, and also on the non destructive measurements is complex. Finally, some challenges for a better use of nondestructive techniques (NDT) are identified.

Key words: concrete, corrosion, damage, environmental degradation, moisture content, nondestructive analysis.

3.1 Deterioration mechanisms and diagnostics of concrete structures

3.1.1 Identifying deterioration in concrete

Although much research is focused on the development of knowledge in the field of concrete deterioration processes and on the improvement of nondestructive evaluation techniques (NDT), a huge gap exists between what is known and what is put into practice. Owing to the progressive ageing of structures in all developed countries, an increasing amount of resources is devoted to the maintenance and repair of buildings, bridges and other types of infrastructure. The challenges are many:

- checking and controlling the 'normal' ageing for usual structures, in order to ensure safety for users and to avoid a drift in maintenance costs,

- reducing the consequences of premature ageing, to avoid problems which would not have been anticipated,
- increasing the lifetime of existing structures, beyond their initially defined service life,
- checking that changes in the conditions of use of the structure (for instance increasing traffic) will not have unacceptable consequences.

Among the information required to improve asset management strategies, the most important is about the material itself: the current concrete condition; its future evolution; the current safety level (using actual information instead of what had been anticipated at the time of design and building); the residual service life. Obtaining such information is not straightforward as it depends on the existing condition of the material and on the deterioration rate, which, in turn, depend both on the material and on its environment, since the deterioration processes often develop under the influence of the natural/anthropic environment. For instance, with regard to the residual service life for corroding reinforced concrete, there are many important factors, including the material microstructure and its consequences on transfer properties, the content of aggressive ions, and the cover depth which plays the role of a barrier against chemical aggression. A reliable nondestructive evaluation of these parameters is therefore a key challenge.

In practice, diagnosis is often required once problems become apparent. Pathology is visible and expertise is required so as to understand and explain, to quantify the extent of damage, to compute the current safety level, and to predict the residual service life. In an ideal world, one would not wait for problems to occur, an optimal knowledge management strategy could be developed, using risk-based maintenance involving optimal data analysis (with data coming from the material, structure and environment). Whether in an ideal or a real-world situation, the same type of information is needed.

3.1.2 Diagnostics and requirements for information

The durability of concrete depends on the resistance it offers to aggression, which can be of physical origin (such as stresses, strains and temperature) or of chemical origin (either from the internal concrete components or from external agents). In both instances, the concrete microstructure plays a fundamental role, since the denser the material, the higher its mechanical strength, and the more efficient it is at preventing the transfer of aggressive agents. As a consequence, any information that can be related to the compactness/porosity of the material microstructure is of interest for diagnostics, even if it is not sufficient by itself.

Useful data can be classified into three groups (Breysse and Abraham, 2005):

- data providing information about the *current material condition*, such as porosity, internal damage and rebar cover depth, which can be measured either directly or indirectly by measuring a property that is sensitive to their variation,
- data providing information about the *deterioration rate*, such as diffusion coefficient and corrosion current,
- data providing information about the *environment*, such as temperature or humidity.

A difficulty arises from the fact that these data are often inter-related. For example, the water content (or concrete saturation rate) depends both on the environmental context and on the actual condition (e.g. porosity) whereas it is also a key factor for future evolution, because transfer properties vary with the water/air content in the paste.

3.1.3 The importance of knowledge about the deterioration processes

The diagnostic has several objectives, including:

- to discriminate between potential causes/explanations of what is visible, so as to understand the problem,
- to find and design solutions for maintenance and repair, on the basis of this understanding. This also requires correct evaluation of the areas within the structure that deserve to be repaired and those that can be left unrepaired, with a limited risk for a given time horizon,
- to identify the value of material parameters and influential parameters (material or environmental) required for a quantified assessment: estimation of residual safety or prediction of residual service life. In this instance, representative values are required for computational analysis, whereas a reliability analysis also requires information about the scattering of these parameters and their time variability.

The characterization of the plain, undamaged material is discussed in the following chapters, therefore we have chosen to focus here on the deterioration processes only. Each process is briefly described and discussed in terms of:

(a) fundamental processes and their causes and mechanisms,
(b) influential factors: either from the material or from the environment,

(c) useful information available regarding the material (in relation to the existing condition and in relation to further development/evolution) and regarding the environment,
(d) usual techniques used for the diagnostic (NDT and others) and information they can provide.

3.2 Physical and mechanical damage processes

Damage in concrete can result from a variety of physical and mechanical origins. It is the reason why we have classified them in the following according to large families of sources, namely overloading, restraining effects, freeze and thaw, and fire. The first instance corresponds to direct damage, when an excessive stress or strain is applied to the material, directly inducing damage. In the three other instances, damage results, at least partially, from some internal cause, because the material may vary in dimensions, thus inducing internal stresses. When these stresses exceed the local material strength, damage occurs or starts to develop.

What is called 'damage'? Concrete being a brittle material, damage always corresponds to the creation and development of microcracks in the material. After a while, these microcracks can coalesce and form one or several macrocracks which can become visible (if they reach the surface) to the naked eye. The damage process is that of the progressive growth of the microcracks network until some ultimate state is reached.

Another meaning of the word 'damage' is that of 'damage mechanics' for which damage is an 'internal variable' whose evolution is linked to the evolution of material properties. For instance, isotropic damage can be measured through the loss of elastic Young's modulus.

In the following section, both meanings (that of micro/macro-cracks and that of mechanical consequences) are considered, because they are inter-related. When assessing the material condition, damage assessment involves, in some instances, the measurement of the density of the microcracks (or the overall averaged loss of stiffness) whereas, in other instances, it means assessing a single macrocrack, whose extension, width or depth can be of interest.

3.2.1 Overloading or imposed strains

Fundamental processes: causes and mechanisms

Overloading, directly caused by a force exceeding what the structure is able to carry or by an excessive displacement (e.g. differential settlements owing to soil movements) is the main source of mechanical damage. It can be the result of static loading, in the short or long term, including creep effects (continuously increasing strain under constant loading). It can also be the result of dynamic loading, resulting from impacts or seismic loading. In both instances, once the load is cancelled, the material retains some memory of the previous overload and cannot go back to its initial state. Internal defects have been created, and they are prone to future evolution. They can also constitute a weak point for further aggressions, as discussed below in relation to durability problems.

Influential factors

The material strength and thus its resistance to overload depends on many factors, such as the composition of the concrete, its age, and the reinforcement ratio for reinforced concrete structures. In addition, the magnitude of the external loading is also a key influential factor.

Useful information

Two levels can be considered for damage assessment:

- if the material is viewed as homogeneous, the question is to assess how its average properties (stiffness, strength, but also capacity to prevent the transfer of water or aggressive agents) are modified as a result of damage;
- if the damage is focused on one or a few specific defects, the question is how to locate them and to identify their geometry (extension, width, depth, etc.), which can condition the structural strength (for instance the stability in case of a large macrocrack) or other parameters such as tightness, which can be a key problem for confinement structures such as reservoirs.

Usual techniques and information provided

Depending on the level of interest, the possible techniques are very different. When distributed damage is looked for, all techniques that are sensitive to averaged material properties can be useful. For instance, the velocity V of longitudinal acoustic waves is directly related to the elastic modulus E through $E = \rho V^2$, where ρ is the volumic mass. Any variation in V can be an indication of a change in stiffness, and, therefore, of damage. However, the problem is more complex because other influential factors, such as the presence of some fluid in pores and cracks can change the velocity and the stiffness (Breysse, 2008).

If the assessment is focused at the scale of macrodefects, the investigation must use techniques that are sensitive to voids and interfaces, such as impact–echo (where a sonic wave reflects on a discontinuity) or radar measurements (for which the radar wave is reflected when it encounters the interface between two media of different properties, such as concrete and air).

Another question is that of the damage monitoring. In this instance, the most common technique is that of acoustic emission, which involves listening to the crack growth: each step in crack propagation releases some energy and emits a sound, which can be recorded and processed in order to track and localize, when several sensors have recorded the same event, the source.

3.2.2 Restraining effects: temperature, shrinkage

Fundamental processes: causes and mechanisms

Concrete may be considered to be a 'living' material, because of its internal evolution and because of its long-term interactions with the environment. Both causes (internal and external) can explain the development of restraining effects, whose magnitude can lead to damage development. Shrinkage is one of the mechanisms involved. Drying of concrete causes an excess of water to evaporate from the capillaries, and the cement paste shrinks to compensate for the surface energy change. This would freely lead to an homogenous decrease of the volume, but it is not possible in practice because, as the drying is taking place through the concrete surfaces, it creates an uneven moisture distribution from the surface and, consequently, a differential shrinkage for the concrete member. This may lead to tensile stresses with resulting crack formation, mainly perpendicular to the surface and whose extent in depth can reach several decimeters in thick structures (Shaw and Xu, 1998). Drying shrinkage is a slow mechanism that can develop over many years for thick specimens. Cracks can also appear in the short term, for instance when concrete dries in a very dry environment.

Another type of shrinkage (autogenous shrinkage) is caused by chemical evolution of the cement paste and exists even when there is no exchange of water with the environment. Shrinkage-induced cracks are usually small and not deep, the depth being limited because the material strength increases with time.

Another mechanism that can induce cracks is thermal cracking at early age. Owing to the exothermal character of the cement hydration, the temperature increases in the core of the concrete, especially in massive structures such as dams and foundations. Because the thermal conductivity of concrete is low, the temperature elevation is not homogeneous and peripheral parts remain at a lower temperature. Because the internal parts tend to expand, as a result of thermal dilation, this creates tensile strains in the peripheral parts and is an additional cause of cracking.

Influential factors

The influential factors include both material factors and environmental factors. For a given material strength, the shrinkage cracks are more severe if:

- the fresh paste contains an excess of water, which will tend to leave the material over time,
- the contrast between concrete and air is high, as is the case with dry hot air.

For both reasons, prevention is the best solution to avoid shrinkage cracks. It often suffices to avoid a too high water/cement ratio and to follow a careful curing, keeping the surface wet such as to avoid evaporation. In practice, this is achieved by spraying or ponding the concrete surface with water, thereby protecting the concrete mass from the ill effects of the ambient conditions. For thermal cracking, the solutions (for massive parts) lie mainly in the use of binders with a lower exothermic power.

Useful information

Apart from purely aesthetic considerations, cracks can have several disadvantages: they can reduce the durability of concrete, but they can also directly affect some serviceability properties, such as tightness (in pipes or reservoir structures). Detecting and quantifying these cracks is therefore important, either during the setting, hydration and hardening (for instance to check that there is no problem) or after the material hardening has ended. In both instances, it is necessary to know the magnitude of cracking. For thermal cracking, the monitoring of the temperature elevation in the massive parts can provide useful data, in order to check that its value is not higher than that calculated during design and that it will not induce cracks.

Usual techniques and information provided

When looking for cracks, because the relevant mechanisms make them appear preferentially at the material surface, a visual inspection is the simplest way to check the integrity of the concrete. This can be replaced (or improved on) by using image analysis or optical methods, or by using an additional source that helps to reveal the cracks, such as flash thermography. However, none of these techniques provides any information on crack depth.

The problem is somewhat different for early-aged cracks, when the material is being monitored in order to check that everything goes well. This can be the case for precast components or for massive parts of structures which require some specific attention from the design stage. Some techniques, such as acoustic emission, can be used (Fontana *et al.*, 2007) to provide information on the development of non-visible cracks in the bulk concrete. Until now, these techniques have been mainly used in laboratory conditions.

3.2.3 Freeze and thaw

Fundamental processes: causes and mechanisms

Freeze and thaw cycles are a major cause of concrete deterioration in the continental type of climatic environment, especially when the surface of the material is not protected with a watertight cover. These cycles can result either in surface scaling and spalling, or in material volumic expansion which usually induces a network of cracks. Both phenomena can occur simultaneously (Balayssac, 2005). On road pavements, the use of de-icing salts can create a thermal shock when the ice melts, and this has consequences on cracking. This is commonly a top-down distress with fractures running parallel with the pavement surface, decreasing in number with depth.

Influential factors

The main influential factor is external temperature, but not all concretes have the same sensitivity to freeze–thaw damage. This sensitivity can be caused by the nature of the aggregates, because susceptible aggregates have a high porosity, made of very small pores. For problems occuring within the cement paste itself, it is known that the porosity and, moreover, the nature of the porous structure is the key factor. Concrete resists freeze–thaw damage when free water can move through capillary pores until reaching ‘bubbles’ where the ice is able to freely expand, without creating excessive internal stresses. The technical solution is known: it consists of adding an air-entraining agent to create a three-dimensional network of small bubbles within the paste, with a regular spacing, thus limiting the development of internal stresses.

Useful information

Since damage is always visible from the surface, its detection and/or quantification are not a problem. Visual inspection is the simpler solution. It provides information about the extent of damage (location and size of damaged zones). It is also important to check to what depth the damage has extended.

3.2.4 Fire

Fundamental processes: causes and mechanisms

Fire is one of the familiar causes of damage of buildings and infrastructures exposed to high temperatures, including accidental and deliberate fires. The main physicochemical changes in the properties of the concrete induced by temperature elevation can be summarized as follows (Neville, 1995; Bazant and Kaplan, 1996; Khoury, 2000):

- the capillary pore water is progressively evaporated, thus the physically combined water is released above 100 °C,
- between 200 and 350 °C, the weight loss results from the loss of water, which becomes chemically linked in calcium silicate hydrates (C–S–H), as well as from the first stage of dehydration of silicate hydrates,
- above 350 °C, portlandite $Ca(OH)_2$ begins to decompose,
- above 500 °C, the weight loss continues at a decreasing rate, as a result of the decomposition of calcium hydroxide (C–H) and (C–S–H), phases are changing in siliceous aggregates,
- above 700 °C, the decarbonation of calcium carbonate occurs and limestone aggregates begin to decompose at 800–990 °C.

The mechanical response of the material is weakened concurrently and the strength reduces, slightly up to 400 °C, and then more noticeably (Colombo and Felicetti, 2007, Chen *et al.*, 2009). However, owing to the low thermal conductivity of concrete, high thermal gradients are created, and these are much more extreme than those discussed in Section 3.2.2. For instance, when submitted to a 'standard fire' (ISO 834 for fire in buildings), after one hour, the temperature reaches 600 °C at 1.5 cm depth, but only 300 °C at 3 cm and 100 °C at 8 cm.

These local changes in the concrete result in the progressive damage. In high-strength and ultra-high-strength concretes, various forms of spalling can have dangerous consequences (Breunese and Fellinger, 2004; HSE, 2005). The ultimate load of the structure is often reached when the elevation of temperature reaches the rebars whose mechanical strength quickly decreases with temperature elevation.

Influential factors

The irreversible decay can significantly depend on the material (mix design or nature of aggregates) and environmental factors (heating and cooling conditions). Structural effects are induced by the fire owing to the non-homogeneity of the loading and to the development of high levels of internal stresses. Thus, the material response depends on:

- the strength of concrete and its ability to maintain strength while the temperature increases,
- the thermal conductivity of the material and its internal porosity: it has been shown that high-strength concrete can exhibit some ‘explosive’ spalling, because when the internal water vaporizes, the internal pressure increases and this can have an explosive effect if the very low porosity of concrete prevents vapour from leaving the material.

Depending on these parameters and on the temperature elevation rate (according to the amount of energy brought by the fire), spalling can be more or less gradual.

Useful information

Assessing the residual strength of fire-damaged concrete is critically important in order to reassess the structure and to decide on the most appropriate repair techniques. The degree of damage can be estimated using visual observation (colour change, cracking and spalling at the surface). However, the colour change depends on the aggregates and comparisons with the same concrete heated in controlled conditions are required for calibration. Owing to the complexity of the development of fire consequences in the material (combining effects of the material thermal conductivity, effects of the heating and cooling history, and structural effects), no fixed relationship can be established between the maximum experienced temperature and the residual concrete strength.

Usual techniques and information provided

Semi-destructive or destructive tests can also provide useful information either about the maximum temperature reached in the material at various depths, or directly about material residual properties (modulus, strength). Research and technical developments in this field are recent, because they have followed some catastrophic fires (Channel Tunnel, Mont-Blanc Tunnel).

Many techniques can be used for damage estimation. However, the main difficulties arise, for fire-damaged concrete, from the fact that the material is highly stratified/layered and that the analysis of measurements must account for that. Thus, analysing local measurements with in-depth averaging assumptions cannot provide a correct assessment of damage. On the other hand, very specialized techniques, such as thermogravimetric analysis or micro-crack density analysis can be used in a point-by-point analysis, but they are very time consuming and do not provide a general overview on the damaged structure.

The possible approaches to this problem have been summarized (LCPC, 2005; Colombo and Felicetti, 2007) and involve:

- either the inspection of the spatial average of the concrete cover, using quick techniques like rebound hammer, or semi-destructive tests (Capo-test, Windsor probe),
- or a point-by-point analysis of specimens taken at different depths,
- or special techiques, mainly based on mechanical wave propagation, for the interpretation of the overall response of the concrete member (Abraham and Derobert, 2003). These techniques can also be combined with other techniques, such as permeation tests, drilling or measurements of Young's modulus on cores, for a more detailed assessment (Felicetti, 2006; Dilek, 2007).

3.2.5 Abrasion erosion

Abrasion–erosion damage is caused by the action of debris rolling and grinding against a concrete surface. It occurs mainly in hydraulic structures and pipes where fluids are circulating. Repeated shocks, like those of floating ice can also induce some abrasion. Concrete surfaces abraded by waterborne debris are generally smooth and may contain localized depressions. Mechanical abrasion is usually characterized by long shallow grooves in the concrete surface and spalling along monolith joints.

Concrete abrasion resistance is primarily dependent upon compressive strength of the concrete. It is also influenced by a number of factors including aggregate properties (whose resistance can be assessed by use of the Los Angeles tests), surface finishing, and type of hardeners or toppings. Use of an additive like fly ash can confer better resistance to the cementitious matrix (Naik *et al.*, 1995). Because the abrasion mechanism is purely a surface mechanism and is easy to assess, it will not be detailed further.

3.3 Chemicophysical damage processes

Many different chemical reactions originating either in the environmental conditions or in the concrete matrix itself can induce concrete deterioration.

3.3.1 Carbonation, chloride penetration and corrosion in reinforced concrete

Fundamental processes: causes and mechanisms

Corrosion is the most important of all the phenomena that cause deterioration of structures (Heckroodt, 2002; Klinghoffer *et al.*, 2000). The US Federal Highway Administration (FHWA, 2002) released a breakthrough study in

2002 on the direct costs associated with metallic corrosion in nearly every US industry sector. Results of the study show that the total annual estimated direct cost of corrosion in the US is a staggering $276 billion, approximately 3.1% of the nation's gross domestic product (GDP). Annual direct costs for highway bridges were estimated to be $8.3 billion (including replacement and maintenance). Indirect costs to the user, such as traffic delays and lost productivity, were estimated to be as high as 10 times that of direct corrosion costs. The corrosion cost for drinking water and sewer systems was estimated to $36 billion. These problems are not limited to the US and evaluations in other western countries lead to similar figures.

Corrosion results from the fact that metals (steel in the case of reinforced concrete) tend towards finding their natural form, which is oxidized. In concrete, the steel is, however, normally protected by the alkalinity of the cement pore solution (pH around 13). At lower pH levels, steel attains a high corrosion potential that leads to passivity, with the formation of a thin, surface film, about two and three nanometers thick, of iron hydroxides, which provides corrosion resistance. The corrosion rate of passivated steel can be less than 1 μm per year. The development of active corrosion in reinforced concrete results from two mechanisms whose common feature is the diffusion of external agents through the pores in the concrete. These mechanisms are the carbonation process and the chloride diffusion process. The physical and chemical modelling of these phenomena is very complex and only basic information is given here. More detailed information is widely available (Bentur *et al.*, 1997; Guillon and Moranville, 2004).

In the ambient atmosphere, concrete is exposed to carbon dioxide. Carbonation occurs when the carbon dioxide enters the concrete: it dissolves in the cement pore solution and forms carbonic acid, H_2CO_3, which reacts with cement hydrates, mainly portlandite $Ca(OH)_2$, producing calcium carbonate, or calcite, $CaCO_3$:

$$Ca(OH)_2 + H_2CO_3 \rightarrow CaCO_3 + 2H_2O$$

Carbonation starts on the surface of the concrete, and propagates inside the concrete, the rate of propagation depending on the diffusion process of carbon dioxide. As the reserve levels of the alkaline solid phases are depleted, a zone of lower pH (the carbonated zone, with values below 10) extends from the surface into concrete. The average magnitude of the carbonation propagation rate is about 20–25 mm in 50 years for a normal concrete under temperate climates. Once the carbonation process reaches the reinforcement, where the pH drops below 13, the passive layer covering the rebars deteriorates and corrosion initiates.

Chloride attack occurs when chloride ions are present, either in the atmosphere (concrete in marine environment) or owing to de-icing salts. Chloride ions enters the concrete by diffusing through the pores or through some surface cracks, for example mechanically induced (see Section 3.2.1) or shrinkage cracks (see Section 3.2.2). When the chloride ions reach a rebar, they can induce corrosion. The adverse interactions between chlorides and the passive film remain unclear. The chlorides are thought to disrupt the passive film, reduce the pH level of the pore solution, or serve as a catalyst for oxidation. Empirical observations have found that when the concentration of chlorides reaches a certain critical value (chloride threshold concentration) the passive film is damaged and corrosion is accelerated (Zhang, 2008). Field experience and research show that on existing structures subjected to chloride ions, a threshold concentration of about 0.026% (by weight of concrete) is sufficient to break down the passive film and subject the reinforcing steel to corrosion. However, the observations are usually done at a macro-scale level and a chloride concentration above the threshold level does not always induce corrosion. There have been many recommendations, both codes and publications, for maximum chloride concentrations. The American Concrete Institute (ACI) recommends the following chloride limits in concrete for new construction, expressed as a percentage by weight of cement: 0.08% for pre-stressed concrete, 0.10% for reinforced concrete in wet conditions and 0.20% for reinforced concrete in dry conditions. Limiting values of 0.4% and 0.1% for reinforced and pre-stressed concrete, respectively, are given by the European standard EN 206-1. The threshold can also be expressed in terms of the relative ratio of the concentration of chloride ions to the concentration of hydroxide ions ($[Cl^-]/[OH^-]$), the critical value being between 0.6 and 1.

The removal of the passive film from reinforcing steel leads to the galvanic corrosion process. Chloride ions within the concrete are usually not distributed uniformly. The steel areas exposed to higher concentrations of chlorides start to corrode. In other areas, the steel remains passive. This uneven distribution results in macro-cell corrosion, in which large anodic sites (for instance on the surface of a bridge deck) and large cathodic sites (on the bottom mat) can be encountered.

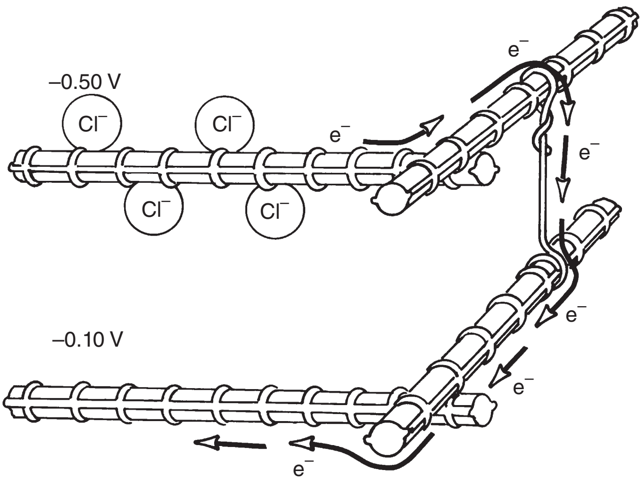
The development of corrosion requires a minimal amount of water and oxygen in the electrolyte, e.g. in the cement pore solution. At anodic sites the metal dissolves:

$$Fe \rightarrow Fe^{2+} + 2e^-$$

At the cathode, oxygen is reduced:

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^-$$

The electrons move through the rebars and hydroxide ions diffuse through solution of the cement in the pores. The concrete acts as the electrolyte and the metallic conductor is provided by wire ties, chair supports, and steel bars. Figure 3.1 illustrates how a macro corrosion cell can develop from



3.1 Differences in chloride ion concentration establish differences in electrical potential (from Daily, 2008).

differences in the concentration of chloride ions (Daily, 2008). Ferrous ions then combine with hydroxide ions to form ferrous hydroxide:

$$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_2$$

While oxygen is available, the reaction goes on:

$$4Fe(OH)_2 + O_2 \rightarrow 2Fe_2O_3.H_2O + 2H_2O$$

Rust, the common name of hydrated hematite $Fe_2O_3.H_2O$, is a complex mixture of several crystalline phases and amorphous phases of ferrous oxides and hydroxides (Balayssac, 2005). The volume of the products of corrosion is much larger than that of initial components and their expansion is constrained by the surrounding concrete. Thus, their development induces internal tensile stresses, which results in cracks around steel rebars when the rust layer reaches a thickness of 0.1 mm. At a later stage, generalized cracking can provoke delamination and spalling (Figs 3.2 and 3.3).

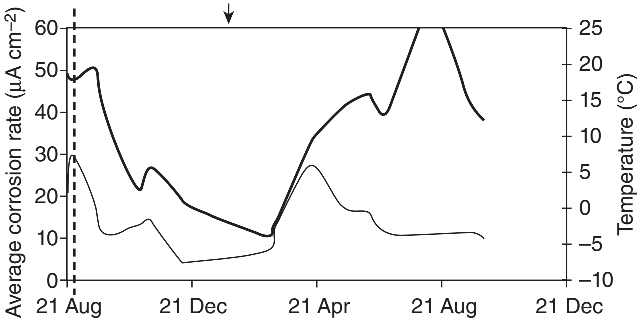
The development of corrosion can also be more localized, developing from areas where the aggressive agents concentration is higher. In this instance (pitting corrosion), the corrosion can develop in depth in the steel, at a much larger rate than generalized corrosion. Because it can drastically reduce the cross-section of the rebar, the structural consequences of pitting corrosion are of primary importance.

Because the rebar is normally in a passive state and the carbon dioxide and chloride ions come from the outside, a certain duration is needed before unfavourable conditions develop at the steel surface. This first stage

3.2 Consequences of corrosion in a concrete wall (from Balayssac, 2005).

3.3 Cracking and spalling owing to corrosion in a marine environment.

normally forms a substantial proportion of the service life before the first maintenance is necessary, and may account for more than 90% of the maintenance-free service life of the concrete. This period is not only dependent on the properties of the cover concrete affecting the rate of transport of the aggressive species, but also on the cover depth. The second stage of the deterioration process involves corrosion propagation: loss of steel section, cracking and spalling development, reduction of the bond capacity between steel and concrete. Once corrosion-induced cracks have been created, they can also change the conditions of corrosion by creating a 'by-pass' between steel and environment, thus accelerating the deterioration process.



3.4 Variation of the corrosion rate with time and temperature (from Ramboll, 2006).

Influential factors

Corrosion initiation and development are both influenced by concrete-related factors and environmental factors. One main environmental factor is oxygen availability: because corrosion can develop only when oxygen is available, this explains the very low corrosion kinetics for underwater concrete. The external concentration of aggressive agents (chloride ions) is a key factor, as is the relative air humidity because moisture favours the transport mechanisms through concrete. Carbonation in the pores of the concrete almost only occurs at a relative humidity (RH) of 40 to 90%. When the RH in the pores is higher than 90% carbon dioxide is not able to enter the pore, and when the RH is lower than 40% the carbon dioxide can not dissolve in the water. This dependence on environmental conditions for the development of corrosion may cause problems for assessment of the material condition because the measurements are also highly dependent on the temperature and humidity at the time of investigation, see Fig. 3.4 (McKenzie, 2005; Ramboll, 2006; Breysse *et al.*, 2007).

For concrete, the two main factors are the cover depth and the concrete porosity. Cover plays a simple role; because carbonation as well as chloride ingress are diffusion processes, their rate of development is a power function of time, with an exponent of about 0.5. This means that doubling the cover multiplies by a factor of four the time before initiation. This provides a simple means for improving the concrete durability. The second factor is porosity. The rate of any transport process depends on the volume fraction, tortuosity and connectivity of the pores. This is determined by factors such as the water/cement ratio (w/c), cement content, cement fineness, cement type, use of cement replacement materials (for example ground granulated blast furnace slag, pulverized fuel ash or silica fume), concrete compaction, and degree of hydration. The concrete mix also has an influence on the ingress of chlorides because the matrix can bind some of the chlorides and thus reduce the pH loss.

Useful information

When assessing corrosion, several sets of parameters can be looked at:

(a) parameters affecting the resistance of the material to corrosion,
(b) parameters qualifying the existing condition of the material,
(c) parameters enabling the future evolution to be assessed.

In addition, information about the environment (temperature, humidity) is welcomed, because it also influences some of the measurements.

For material resistance, the two main parameters are the cover depth and the concrete diffusivity (because diffusivity measurements cannot easily be performed on site, any data that can be related to the porosity are of interest). The carbonation diffusivity D can be estimated by measuring the carbonation depth x_c at various ages t. These parameters are related by Fick's law:

$$x_c = k\,(Dt)^{0.5}$$

This law is only approximate, because there is a coupling between chemical reactions and the diffusion process and it is only valid in saturated concrete. However, it can be used as a first step, for identifying the value of the product k^2D, which enables the future evolution of x_c to be predicted. Regarding the existing condition, e.g. how advanced the corrosion is, required parameters are the carbonation depth, the chloride content at various depths (chloride profile) and the degree of corrosion, which can be evaluated from its effect on electrical potential and current density. For evaluation of the future evolution, or the residual service life, one needs to know how much of the steel section remains. This implies that the rebar diameter is known.

Usual techniques and information provided

Because the development of the corrosion depends on many factors, a wide range of techniques can be used to enable the material to be assessed. The techniques include:

- measurements regarding the rebar (cover depth, diameter), based on electromagnetic measurements,
- minimally destructive measurements, such as small drillings, to measure the carbonation depth (pH measurement given by change in colour) and to sample the cement paste at various depths (chloride content is usually measured in the laboratory as described in chapter 10, from the chemical analysis of powder),

- measurements regarding the porosity of the concrete, which can be evaluated (for instance) through its electrical conductivity (Lataste *et al.*, 2005),
- electrochemical measurement, such as half cell potential measurements (Andrade and Martinez, 2003), which provide an indication of the likelihood of corrosion activity at the time of testing, through a value of electric potential (ASTM standard C876-91 relates the measured value to the probability of corrosion), and the real activity of corrosion, by measuring the corrosion current (which results from the movement of ions in the cement paste).

Despite its many weaknesses, electrical conductivity measurements have been highlighted by Song and Saraswathy (2007) as being useful in the estimatation of both the initiation and propagation periods. The main advantage is that resistivity is an inexpensive NDT that can be used for routine quality control. For the time to corrosion onset, the electrical resistivity is an indicator of the porosity and its connectivity and, after initiation, it can be used to model the transport processes.

Specific attention has to be paid to spatial and time variability while assessing the structure (Breysse *et al.*, 2007):

- spatial variability can be high, either owing to the environment or to the material itself, and it is recommended that a wide field technique is used, to map corrosion and to locate the areas of high probability of corrosion or of high activity,
- time variability has a great influence, both on the corrosion kinetics and on the measurements themselves. It would be ideal to use long-term monitoring of the structure to quantify the real variations of corrosion along time, but this requires embedded sensors, which means a higher cost and which is possible only in the areas where a problem has been identified (or is expected).

3.3.2 Alkali–aggregate reaction

Several chemical deterioration processes can develop from the concrete mix itself, owing to its internal constituents. The best known is alkali–silica reaction.

Fundamental processes: causes and mechanisms

Alkali–aggregate reaction (AAR, also named alkali–silica reaction, ASR) occurs between cement alkalis in the pore water of the concrete and some siliceous compounds in aggregates producing a type of gel. When in contact with water, the gels swell causing tensile stresses and ultimately cracking

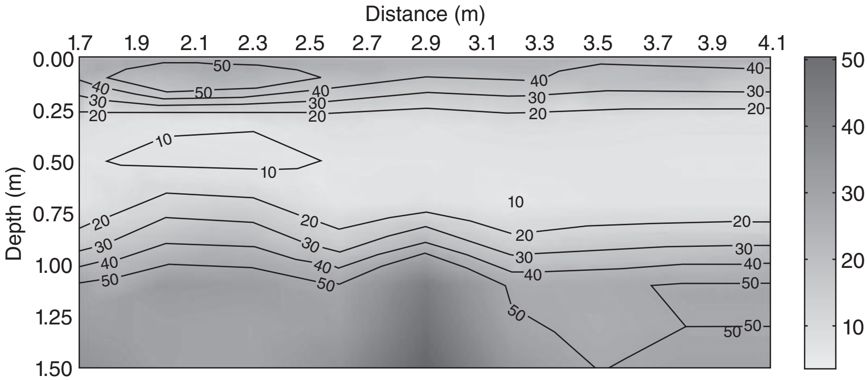
3.5 Surface crack network owing to AAR (from Balayssac, 2005).

(internal cracks in the aggregates, microcracking around aggregates, and separation between aggregates and cement paste), the final result of which is often a crack network on the concrete surface (Fig. 3.5). The cracks form a mesh whose size is related to the crack depth: a large mesh of about 30–40 cm corresponds to a crack depth above 10 cm. The consequence, apart from reduced durability owing to cracking, is primarily a reduced tensile strength of concrete. In massive structures, material volumic expansion generates internal stresses which can provoke structural disorders. In reinforced concrete, active and passive rebars can be overloaded, having possible consequences on the overall structural safety. The first historical cases were noted in 1940 in Californian pavements, then in many other countries, including Europe, with a first case in Denmark in 1950. In France, the case of the Chambon dam is famous, since the only remedy was to saw the structure to release the overly intense internal stresses (Cottin *et al.*, 2003; Kert, 2008).

The detrimental expansion takes several years to develop in field concrete structures, thus the potential risk is often evaluated in the laboratory under accelerated conditions. A pre-requisite for AAR is high moisture levels. When a structure is suspected to have AAR, both the reactivity of the aggregates and humidity levels in concrete need to be examined, and the development of cracking closely monitored. It should be noted that the development of cracking may accelerate after some years.

Influential factors: useful information and techniques

As shown above, the reasons for AAR development are related to the material constituents (mineralogy of aggregates) and the constant presence



3.6 Estimation of the Young's modulus (in GPa) within the concrete (from Al Wardany *et al.*, 2009).

of humidity. Once a structure has been recognized as subject to AAR there is no satisfactory remedial solution, because the source of the problem is the material itself. The only possible action is to cancel or limit its consequences at a structural level, for instance by releasing the internal stresses.

To define the magnitude and volume extent of the problem, NDT can be used, followed by laboratory measurements and experiments. Laboratory tests help in quantifying the dilation potential, and in predicting future disorders. They are the basis for designing structural solutions.

The structural mapping can be performed by using techniques which are sensitive to changes in material damage. As it is known that the velocity of acoustic waves decreases when damage increases, such a technique can be useful. Surface wave testing has, for instance, been performed by Al Wardany *et al.* (2009) in a large hydraulic structure. The investigated structure was located in eastern Canada, and had been in service since 1959. AAR has developed over the years under conditions of saturation, warm summer temperature and high content of alkalis. The structure shows various levels of expansion and cracks in concrete. After inversion, the wave velocity has been mapped in the volume and the spatial variability of the Young's modulus has been deduced (Fig. 3.6).

3.3.3 Sulfate attack

Fundamental processes: causes and mechanisms

Sulfate attack is another possible deterioration mechanism of concrete. It can have endogenous origin (developing without any contribution from the

3.7 Cracking pattern in a bridge suffering from internal sulfatic attack (from Germain, 2008).

environment) or exogenous origins (such as sulfates contained in the soils or in liquids) (Germain, 2008; Neville, 2004). In both cases, the consequence is some volume expansion owing to the delayed formation of ettringite, which is an expansive component. The internal sulfate attack is characterized by a delayed mobilization of cement sulfates, and it leads to the generalized deterioration of the concrete. The main cause is a high elevation of the temperature, which can be encountered in the case of massive structures (see Section 3.2.2) or during precasting while using steam curing. The word 'delayed' indicates that ettringite could not form (as is the usual process) during the cement hydration, because of an overly elevated temperature (ettringite is destroyed over 70 °C). It then appears several weeks, months or years after the casting. Damage to the concrete occurs when the ettringite crystals exert an expansive force within the concrete as they grow. The material volume expansions, similarly to what happens with AAR, creates a crack network on the structure surface (Fig. 3.7) (Carles-Gibergues and Hornain, 2008).

The first case of internal sulfate attack was identified in 1987 in Finland, in precast concrete specimens for railway tracks, although external sulfate attack had been recognized since 1887 with problems owing to interaction with gypsum on walls in Paris. External sulfate attack is a chemical breakdown mechanism where sulfate ions from an external source (underground water, sea water, some earthworks) attack components of the cement paste. Such attack can occur when concrete is in contact with sulfate-containing water, e.g. seawater, swamp water, ground water or sewage water. The often massive formation of gypsum and ettringite formed during the external sulfate attack may cause concrete to crack and scale. For external sulfate attack, the reaction propagates from the surface towards the concrete core. A specific context of sulfate attack is that of the sewer system where biological processes and unsufficient air ventilation can provoke the accumulation of hydrogen sulfide (H_2S) which, after transformation by sulfo bacteria in sulfuric acid (H_2SO_4), attacks the cement paste, leachates the portlandite and also forms secondary ettringite.

The apparent pathology of sulfate attack is similar to that of AAR, thus preventing the two phenomena being distinguished without a microstructural analysis.

Influential factors: useful information and techniques

The causes and mechanisms of internal sulfate attack are not fully understood and remain the topic of many research studies. It seems, however, that several factors must be present together for the reaction to develop, thus explaining the relatively low number of structures which are attacked. The main parameters are high temperature, the water, sulfate and aluminate contents of the cement, and the alkali content of the concrete.

The fact that the concrete (for internal sulfate attack) has been subjected to high temperature is a key factor: the sulfate attack develops in parts where the heat created during hydration could only partly be evacuated out of the concrete. This is the case in massive pieces, which have been cast during summer. A constant external high humidity level is also a favourable factor. The concrete mix also has an effect (Carles-Gibergues and Hornain, 2008): alkali content, SO_3 and Al_2O_3 content in the cement, and cement content, amongst other parameters, being important.

Similarly to AAR, once a structure has been identified as subjected to sulfate attack there is no satisfactory remedial solution, because the source of the problem is the material itself. The only possible action is to cancel or limit its consequences at a structural level, for instance by releasing the internal stresses by sawing (thus, the best response to the possible problem is to design the concrete in such a way that there is no risk of sulfate attack, but prediction of field performance using laboratory studies is difficult (Santhanam *et al.*, 2001).

It is necessary first to confirm that it is really a sulfate attack, through microscopic analysis of the hydration products, checking for the presence of delayed ettringite. Thus, the magnitude and volume extent of the problem can be evaluated. It is possible to use non-destructive techniques that are sensitive to changes in material damage (distributed cracking). For instance, it has been shown (Ferraro, 2003) that acoustic waves velocity decreases when sulfate attack develops. This influence is similar to that noted in Fig. 3.6 for AAR.

3.3.4 Other chemical attack mechanisms

Under its various forms (rain, snow, underground water, seawater), water is usually present in the direct environment of reinforced concrete structures. As explained earlier, concrete is an alkaline medium, with a pH around 13, much higher than the pH of the environment. When external water is in contact with concrete, it can dissolve portlandite (and eventually other hydrates) bringing out the dissolved salts, and this process continues as long as the water is renewed.

The dissolution power of water is higher if it contains carbon dioxide, and if a pure Portland cement is used. White efflorescences on the concrete surface are sometimes the sign of leaching. An OCDE investigation had shown that leaching is the second more common deterioration process in concrete after corrosion (OCDE, 1989). The lixiviation process progressively increases the porosity of the concrete and further reduces its strength. Because porosity has a large influence on the main deterioration processes, lixiviation affects the overall durability of concrete.

With respect to other potential chemical attacks, concrete is resistant to most natural environments and many chemicals. The effect of sulfates and chlorides has been discussed earlier. Ammonium nitrate is another usually harmful product for concrete. Ammonium nitrate under the form of a solution, dust or vapour, presents a long-term aggressive environment for reinforced concrete. The primary deterioration mechanism is the reaction of ammonium nitrate with calcium hydroxide in the cement paste which increases the porosity and decreases the alkalinity. The calcium nitrate resulting from this then reacts with hydrated calcium aluminate, present in cement, to form calcium nitroaluminate, which has a higher volume. This reaction leads to an expansion of the weak matrix and subsequent bursting of contaminated layers.

Ammonium nitrate also promotes stress corrosion of steel reinforcement. Ammonium nitrate attack is generally first seen as a removal of surface dust (known as laitance) followed by a loss of aggregate in the weak cement matrix that eventually exposes the reinforcing bars. Where wetting and drying exist, the laitance may not be removed and the apparently sound concrete surface may simply burst. The degradation increases with ammonium nitrate concentration. Just 0.5% of ammonium nitrate by weight of cement appears sufficient to cause considerable damage.

3.4 Synthesis and conclusions

3.4.1 Synthetic view of deterioration mechanisms and their consequences

Concrete durability is characterized by its resistance to weathering action, chemical attack, and other degradation processes. We have discussed in this chapter the following physical and chemical degradation mechanisms: mechanical loads (owing to external or internal loadings), freeze–thaw damage, fire corrosion of reinforcing steel either resulting from carbonation of concrete or from chlorides, alkali–aggregate reactions, and sulfate attack. In practice, several degradation mechanisms can act simultaneously with possible synergistic effects.

It has been shown that many common points exist regarding the influential factors (such as concrete porosity and moisture) and the resultant patterns of the deterioration processes. For instance, a chemical attack often begins with the intrusion of the aggressive agent, which reacts with the cement hydrates and modifies the matrix (e.g. by dissolution). The porosity then increases and the strength decreases. As a second result, some products can precipitate and, when they are expansive, they induce internal stresses and cracking. Table 3.1 (adapted from Balayssac, 2005) summarizes the mechanisms that have been presented above, their main consequences and what type of information is looked for when assessment is required. The required information can be obtained through laboratory measurements performed on samples cored from the structure (measuring porosity, stiffness and strength, the quantity of chlorides or performing microscopic analysis as detailed in chapter 8), but the use of NDT can also provide a lot of useful data.

The last column in Table 3.1 contains items related to the actual material condition (such as porosity, rebar cover depth and internal damage), as well as data that influence the future evolution (such as corrosion rate and potential for volume change). Environmental parameters are important for several reasons:

- a good knowledge of the environment is often necessary for an accurate assessment of the damage mechanisms. It has also been seen that humidity has a high influence on several deterioration mechanisms (such as AAR, chloride diffusion and sulfate attack);
- many NDT are highly sensitive to variations of external temperature or humidity, because the concrete tends to be in equilibrium with external conditions. This is the case for electrochemical measurements, and also for most NDT that provide indirect information about stiffness or strength (such as ultrasonic pulse velocity (UPV), electrical conductivity and dielectrical permittivity). For this reason, it can be said that, up to

Table 3.1 Synthesis of main deterioration mechanisms, consequences and required information

Mechanism	Consequence on concrete	What is looked for?
Overloading Restraining effects (temperature, shrinkage)	Damage, cracking	• if distributed damage: crack density, residual stiffness and strength • if localized cracking: location, width, depth
Freeze–thaw cycles	Scaling, spalling, delamination	• delaminating areas • depth of delamination
Fire	Strength decrease, spalling	• depth reached by fire effects • residual strength at various depths
Abrasion–erosion	Material loss	• residual strength of surface layer
Carbonation	Increase in density, depassivation of steel, thus rebar corrosion	• carbonation depth • if corrosion: localization of active corrosion areas, corrosion rate
Chloride attack	Rebar corrosion	• chloride content, chloride profile • if corrosion: localization of active corrosion areas, corrosion rate
Alkali–aggregate reaction Sulfate attack	Internal expansion, generalized cracking	• potential for future volume change • residual stiffness and strength
Leaching	Cement paste dissolution, increase in porosity	• residual strength, porosity
Ammonium nitrate attack	Deterioration of the cement paste, spalling, rebar corrosion	• depth of the attack • if corrosion: localization of active corrosion areas, corrosion rate

now, no NDT exists that would be totally validated and could be used with closed-eyes as a 'standard' for assessment of concrete structures, even if electrochemical techniques have been standardized for corrosion diagnostics. The methodology of calibration of NDT results remains an open question.

3.4.2 Main challenges for NDT in concrete assessment

The choice of adapted techniques during the investigation is based on the following properties:

- *resolution of the technique*, which must be sensitive to any variation of the potential influential factor, so that any variation in the measurement provides information about the possible variation of the influential factor;
- *discriminination*, because it is better to use a technique that is not sensitive to 'everything', to allow discrimination between a series of possible explanations. For instance, a usual question is that of the magnitude of the variation which can be considered as a signal and not simply as a noise.

Regarding a material like concrete, these requirements can be translated in terms of:

- *ability to quantify the material properties*; each NDT works because it is sensitive to some concrete physical property (such as the structure of the material porosity) but the assessor often looks for 'engineering properties' (such as stiffness and strength). The relation between the NDT result and the mechanical property is not straightforward and it requires calibration. Because the real structure is never exactly similar to the material on which calibration was made, the question of quantification remains open (Breysse *et al.*, 2008a);
- *ability to uncouple effects* between the influence of the real material properties (whose assessment is looked for) and those of other parameters (environmental parameters like temperature and humidity).

Shaw has pointed out the 'humidity paradox' (Shaw and Xu, 1998), which comes from the fact that the role of water is twofold:

- on the one hand, the moisture content of the concrete governs its durability. Mehta *et al.* (1992) observed that water is 'at the heart of most of the physical and chemical causes underlying the deterioration of concrete structures'. It determines, among others, the differential shrinkage during the drying process, the risk of corrosion, and the rate of alkali–aggregate reaction,
- on the other hand, moisture variations affect testing performance as the speed and penetration ability of acoustic and electromagnetic pulses, or the criteria used in evaluating electrochemical test results.

Thus, one can say that significant challenges for NDT are:

- to be able to determine the moisture condition of massive concrete members on site (including its spatial and temporal variations),
- to be able to use this information in processing measurement data, in order to uncouple the effects of the environmental conditions, and to derive the actual material properties.

It has been recently shown (Breysse, 2008) that the question is similar for other building materials like stone and timber in which water is both an influential parameter in deterioration mechanisms and an influential factor for NDT. In all these situations, NDT encounters the same problems, owing to uncertainties in measurements, to material spatial variability and to the effects of environmental parameters: each NDT measurement can be sensitive to the real material condition (e.g. porosity or chloride content) but it is, at the same time, sensitive to the moisture content (and to temperature), thus making the assessment more difficult. This question has been addressed by focusing on the sensitivity of UPV to water/moisture content, whose variations can be either a result of damage (because an increased porosity can contain more water) or indications of a context favouring damage.

It has also been shown (Breysse *et al.*, 2008b), with data obtained on concrete, that it is possible, by a relevant choice of NDT, to quantify material and engineering properties like stiffness or strength, and to provide an estimate of their degree of uncertainty. This question, however, opens a wide field of potential (and required) improvements. In the second part of this book, it will be shown in several cases how the combination of well chosen techniques can contribute to improving the assessment, even if a more systematic combination process remains to be formalized.

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