# Degradation, corrosion and analysis of the durability of concrete structures.

## 1 Introduction

The problem of corrosion is one of the most important issues that have to be consider in the design phase of a structure. A wrong assessment of the behavior of reinforced concrete subjected to corrosion could, in fact, effect drastically the assessment of the durability of a structure.

In structures designed and built in order to resist corrosion, the effects of deterioration are not important and usually are localized in some zones easily fixable. The problem, instead, is for old structure where, either during the design phase or during the construction phase, the problem of corrosion has not been considered enough. In these designs, usually, during the life of the structure, the measure of the security of the structure itself has to keep into account the effects of deterioration due to aggressive agents.

For concrete structures, in fact, for deterioration it is meant the local or global losses of continuity and a consequent reduction of the resistant sectional area.

The goal of this paper is, first of all, to have a general idea of all the processes involved in the corrosion and the deterioration of reinforced concrete. Once the principal processes will be understood, the main processes involved in the corrosion of the rebars will be explained in more depth and finally there will be an overview of the major theories proposed to assess the life span of a deteriorated structure.

## 2 Concrete deterioration

The principal degradation processes involved during the service life of reinforced concrete structures can be divided into 5 major categories:

### 2.1. Phisical processes

*1.1: Icing -deicing cycles.*

When the temperature reaches low values the water contained in h concrete's pores can ice with a consequent increase of its volume (almost 9%). When the phenomenon is repeated several times the tension stresses can lead to the cracking of the concrete paste.

Usually these phenomena involve in a first moment the external part of concrete given the low coefficient of thermal transmission of concrete, but when the damage is present in the external part of the structure it can reach the core of the section.

One of the theories proposed to study this degradation process is the theory of the hydraulic pressure (Powers) and it explains the damage due to the ice de-ice cycle assuming that the formation of ice pushes the remaining water in the inner concrete causing an increasing in the water pressure in the pores.

*1.2: Fire.*

When the temperature rises over 100, 150 degrees Celsius, after an initial expansion, the concrete paste reduces its dimensions due to thermal decomposition of the hydrates components of the paste itself. The problem with this volume reduction is the formation of stresses on the interface with the aggregates. With their silicon nature, in fact, the aggregates tend to increase their volume instead of reducing it.

So, the firsts cracking begin on the interface between concrete and aggregates but if the temperature keeps on growing the structures can be subject to additional problems.

When the temperature reaches 500 °C, in fact, due to the high thermal conductivity of the rebars compared to the one of concrete the rebars tend to deform more than the surrounding concrete causing other stresses between rebars and concrete.

## 2.2. Chemical processes

*2.1: Sulphatic degradation.*

This kind of degradation occurs when concrete is in contacts with waters or grounds containing sulphates elements or when the aggregates contain sulphate. The reactions of the sulphates with the hydrate components present in the concrete paste cause the formation of products with higher molecular volume. When the production of these products is enough, it is possible to observe the formation of micro cracking due to the presence of bigger molecules.

*2.2: Degradation due to seawaters.*

The deterioration due to seawaters depends on the position of the structure respect to the sea level and it is concentrated almost entirely in the zone between the high and the low tide.

This degradation can be:

*MECHANIC*, due to the dynamic action of high and low tides that can produce superficial erosion.

*CHEMICAL*, due to the crystallization of the salts present in the water into the concrete pores.

## 2.3. Mechanical processes

The mechanical processes involved in the degradation of concrete are several but, the most important can be summarize into three different groups:

*1: ABRASION, superficial damage due to the friction with a stronger material*

*2: EROSION, CAVITATION, IMPACT especially for structures build into a water stream*

### 2.4. Structural processes

Those deterioration processes are the most common and usually their assessment is taken into account during the stages of the design. In this category, in fact we can find overloads, settlements and Fatigue.

### 2.5. Rebars Corrosion

Given the complexity of this mechanism it will be exposed separately in the next paragraphs.

In order to summarize the principle causes of degradation of a reinforced concrete structure it is probably helpful to use the following chart: flake

| | Degradation Processes | | Degradation effects |
|---|---|---|---|
| 1 | **Physical Processes** Thermal variation: | Naturals: Icing deicing cycles Artificial: Fire | Micro cracking Spalling Loss of resistance |
| 2 | **Chemical Processes** Action: | Sulphatic From waters Reactions alkali-aggregates | Micro cracking Concrete desegregation Superficial erosion Loss of resistance |
| 3 | **Mechanical Processes** | Abrasion Erosion Cavitation Impact | Flaking |
| 4 | **Structural Processes** | Overloads Settlements Fatigue | Micro cracking |
| 5 | **Rebars Corrosion** | Carbonation Chlorides Degradation | Spalling Reduction of rebars sections |

# 3 Rebars corrosion.

If the concrete structure is well designed and built, the rebars are in a perfect environment to resist corrosion. Concrete, in fact is an alkaline environment with pH more than 13. This alkaline environment produces a tiny film (just few molecular layers) on the rebars that can prevent the propagation of oxidation.

During the life of the structure the rebars have two completely different behaviors. In the first stage the film produced by the basic environment let the rebars to be completely non corroded. Only when the film is broken the propagation of corrosion can begin. Usually the local failure of the film is due to three different reasons:

1) The concrete's alkalinity is neutralized by the presence of carbon dioxide present in the environment that let the alkalinity drop from 13 to 9. (Carbonation)
2) The presence of chlorides in the environment. When the chlorides are more than 0.4-1% of the total concrete weight the film on the rebars is usually damaged
3) The presence of electric fields in the structure

Once the oxide film covering the rebars is broken the behavior of the corrosion is linear with time. That means that if we plot the depth of corrosion versus time we will have a graph like [Pedeferri 1987]
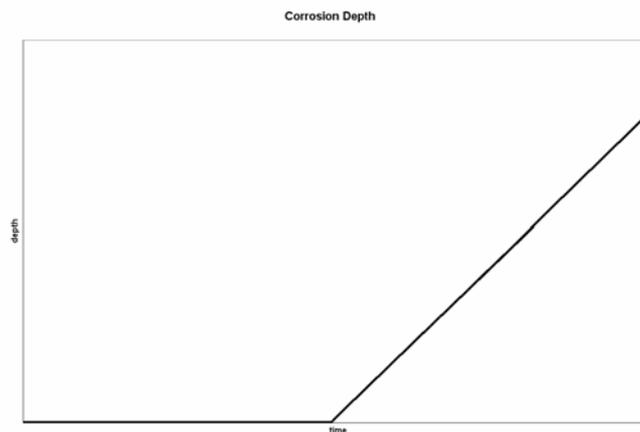


## 3.1. Corrosion Velocity

Once the corrosion of the rebars has begun the most important factor to assess the gravity of the corrosion is its velocity. The corrosion velocity is usually expressed as the penetration velocity and it is expressed in µm/year.

Until the penetration velocity is less than 1.5-2 µm/year the consequences of corrosion are irrelevant compared to the normal design life of the structure. The corrosion begins to be a problem when the penetration velocity reaches values higher than 2 µm/year. At this rate, in fact, the corrosion products accumulate on the interface between rebars and the surrounding concrete, causing a decreasing in the friction between the two, the formation of cracks in the concrete and even spalling phenomena.

Indicatively the ranges of penetration velocity can vary between values less than 2 µm/year to values higher than 100 µm/year

## 3.2. Corrosion due to Carbonation

As mentioned before, concrete is the ideal environment for the rebars. This is due to the fact that usually the pH of concrete is very alkaline and prevents the corrosion of rebars passivating them. The problem rises when the pH of concrete decreases below values around 11.

Concrete structures are always in contact with atmosphere, which contains carbon dioxide in a range of values between 0.04%(for country) and 0.2%(for cities). The effect of carbon dioxide on concrete is to decrease the porosity and to increase the mechanical strength of the material. From this point of view it would seem that the effect of carbon dioxide helps a concrete structure instead of damaging it.

The only problem is the effect that CO2 has on the pH of concrete.

From the reaction:

$$CO_2 + Ca(OH)_2 = CaCO_3 + H_2O$$
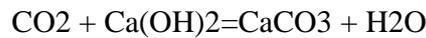
due to the consumption of ions $OH^-$, the pH of concrete decreases from normal values (between 13 and 14) to values near to neutrality and causes the braking of the passive film that covers the rebars.

To study the increasing of the width of the section interested by Carbonation a simple law has been proposed: $s = K \cdot t^{\frac{1}{n}}$

Where:

s is the width expressed in millimeters of cross section interested by Carbonation,

t is the exposure time expressed in years

K is the carbonation coefficient, which depends on several environmental factors like humidity, temperature and CO2 concentration and several material properties like alkalinity and porosity.

For normal concretes, usually $n$ is taken to be equal to 2 and the previous equation becomes a simple parabolic equation in the form:
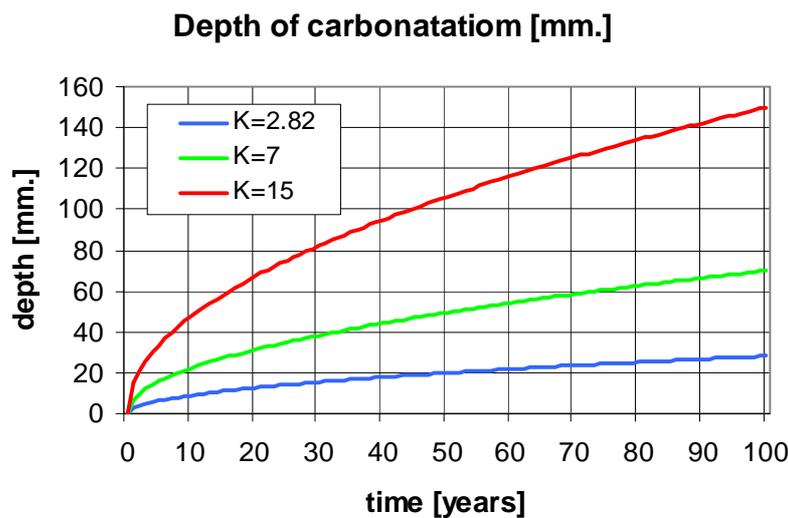
$$s = K \cdot \sqrt{t}$$

**Depth of carbonatatiom [mm.]**



**Figure 2:Depth of Carbonated Concrete**

From the graph above it is possible to have an idea of the depth of Carbonation during time. It is possible to notice that in humid environments with high temperature (K=15) the depth of carbonation could reach values of 4 cm. In less than ten years and, considering the fact that usually rebars are placed around 5 cm from the outside border of a section, the problem of corrosion due to carbonation of concrete could be a main problem after only ten years of life of a structure. [P.Pedeferri, L.Bertolini,2000]

During the design phase it is necessary to ensure a concrete that will allow a velocity of carbonatation at least less than 1mm. per year [C.L.Page, 1986]. That means that the carbonation process will involve the rebars after an approximate period of 50 years which is the normal value of design life for common structures.

### 3.3. Corrosion due to Chlorides

The other main problem that can cause the corrosion of the rebars inside the concrete is the excessive presence of chlorides in the environment. This high percentage of chlorides can be either in the external environment like in water, air and grounds or inside the concrete when the material used contains chlorides (for example if the aggregates are made of marine sand not accurately washed).

If we suppose that the structure is not already corroded by carbonation, the corrosion due to chlorides is totally different from the previous one. In this case, in fact, it is possible to observe that the corrosion of rebars is localized to small zones (pitting) and only rarely involves large areas of steel.

This kind of corrosion can begin only when the concentration of chlorides ion $Cl^-$ with the respect to the concentration of ions $OH^-$, reaches a critical value $C_{cr}$ which is the value that, commonly, is used to estimate the design life of the structure. The life span of a structure under the action of chlorides degradation is, in fact, the time $t$ in which the concentration of the ions $CL^-$ reaches the critical value.

The process involved in this kind of degradation is an electrochemical process, which involves either the rebars or the adjacent concrete.

The effect of chloride, in the first step of this process, is to neutralize a bit portion of the film which covers the rebars and to let the rebars to become anodes.

Once the steel is anodized it keeps on providing electrons ($e^-$) to the boundary surface between concrete and steel with the consequence of an increased production of ions $Cl^-$.

The concentration of chlorides in time can be described using the second Fick's law which describes the non-stationary diffusive processes in porous media.

In the case of homogeneous material, where the diffusivity D is constant, the second Fick's law can be written as:

$$\nabla^2 C = \frac{1}{D} \cdot \frac{\partial C}{\partial t} \tag{0.1}$$

Where C(x,y,z) is the variation of the concentration of the adsorbed species.

D is the diffusivity matrix, given by the equation:

$$J = -D\nabla C$$

In which J is the flux of adsorbed mass in the media.

In reality only for completely saturated concretes the diffusion process can be descries with the application of the second Fick's law. For concrete, not completely saturated with water, the experience shows that it is still possible to use the second Fick's law but with an effective diffusivity matrix $D_{ce}$

By solving equation (0.1) with the effective diffusivity it is possible to obtain the solution:

$$C_x(t) = C_s \left( 1 - erf \frac{x}{2 \cdot \sqrt{D_{ce} \cdot t}} \right) \qquad (0.2)$$

where:

t is time,

x is the depth in the cross section,

Cx is the content of chlorides at depth x at time t,

Cs is the surface content of chlorides.

With equation (0.2) it is possible to estimate the time in which the concentration of chlorides will reach the critical value and will begin to break the film around the rebars. As Mentioned before, the corrosion due to the presence of chlorides is localized to really small areas of steel. Only when there is the synergic effect of carbonation and chlorides action the process can involve bigger zone of concrete

## 4 Design life Assessment

There are several different methods to assess the life span of a structure subjected to degradation. All these methods provide equation and empirical parameters to determine the time $t$ in which the structure will reach a level of deterioration high enough to compromise its serviceability or its stability; the difficulties of most of them are linked to the presence of many parameters of difficult determination. The method proposed from the Japanese group of the JSCE, for example, uses 80 parameters correlated to the environment, the kind of steel and the kind of concrete used, to assess the durability of a structure.

The methods expressed in this paper are two of the most commonly used during the design of a structure given their simplicity and the low number of parameter associated with their use.

### 4.1. Carbonated Structures

Usually, the estimate of the durability of carbonated structures, is related to the time in which the depth of the corrosion in the rebars reaches an imposed limit value ($D^{cr}$); an alternative way to see the problem is to find the time $t$ in which the rebar experience a reduction of the cross sectional area bigger than an imposed value.

The decision of the limit value it's not always easy: This value, in fact, depends on the concrete used, on the cover depth, on the environmental conditions and on the type of rebars. Without precise information about the structure, usually, this value is set to be 100 µm because, from testing, it has been shown that the value in which, generally, rebars loose their functionality is in the range of 50-200 µm.

The equation proposed to find the life span of a structure subjected to the only action of carbonation is:

$$t = t_i + t_p$$

Where:

$t_i$ is the time before the beginning of corrosion and,

$t_p$ is the time that is necessary to reach the limit corrosion depth in the rebars.

As exposed in paragraph 3.2 the time $t_i$ in which corrosion begins to take place, is function of the depth of the carbonation process. At the time $t$ in which the carbonation

depth reaches the depth of the rebars the process of corrosion can start and this time is usually taken to be $t_i$. Using the parabolic equation exposed in the previous paragraph,

then: $t_i = \left(\dfrac{d}{K}\right)^2$ where $d$ is the cover depth and $K$ the carbonation coefficient.

For the time $t_p$, the equation proposed is, instead: $t_p = \dfrac{D^{cr}}{V^{corr}}$ where $D^{cr}$ is the imposed limit value of the depth of the corrosion and $V^{corr}$ is the velocity of the corrosive process. Therefore:

$$t = t_i + t_p = \left(\frac{d}{K}\right)^2 + \frac{D^{cr}}{V^{corr}}$$

From this equation, given the dependency of the parameter $K$ on the kind of cement used, it is possible to find the cement quality necessary to provide the life span desired for the structure.

## 4.2. Structures Subjected to the action of Chlorides.

The assessment of the life span of a structure subjected to the action of chlorides follows a procedure slightly different to the one explained for the carbonation process. The difference is that, in this case, the expected design life depends only on the time in which the corrosive process begins and not on the time in which the process develops. This difference is due to the fact that the corrosion due to chlorides is much faster and its determination is always difficult and uncertain.

As explained in paragraph 3.3, this kind of corrosion begins when the concentration of chlorides reaches a critical value. Using equation (0.2) it is possible to know the time $t$ in which the concentration of chlorides reaches the critical value.

It is also possible to use equation (0.2) in order to find the effective diffusivity $D_{ce}$ by imposing an expected time $t$ in which the concentration of chlorides will reach $C_{cr}$. Then, by relating the effective diffusion with the concrete used it would be possible to find the correct concrete to be used for an imposed design life.

One of the most commonly used methods is a graphical method proposed by Bamforth. This method uses the following graphs as follow:

1. On the life span axis in the bottom right graph, a design life is chosen and from that design life a vertical line should be drawn
2. A horizontal line is traced from the cover depth until the intersection with line 1
3. At the intersection of these two lines, a line is traced parallel to the nearest curve until it reaches the horizontal at 50 mm cover depth.
4. From this new point a vertical line is traced till the life span axis.
5. From the bottom left graph it is possible to find the surface concentration of chlorides as a function of the cement content in the concrete.
6. From that surface concentration, using the top left graph, a vertical line is drawn until the curve that describes the required percentage in mass of the chlorides is reached
7. From there it is possible to draw a horizontal line to find the critical content of chlorides.
8. Using the value found in 7. and the value found in point 4 it is possible to find the effective diffusion $D_{ce}$ required for an imposed life span (point 1)
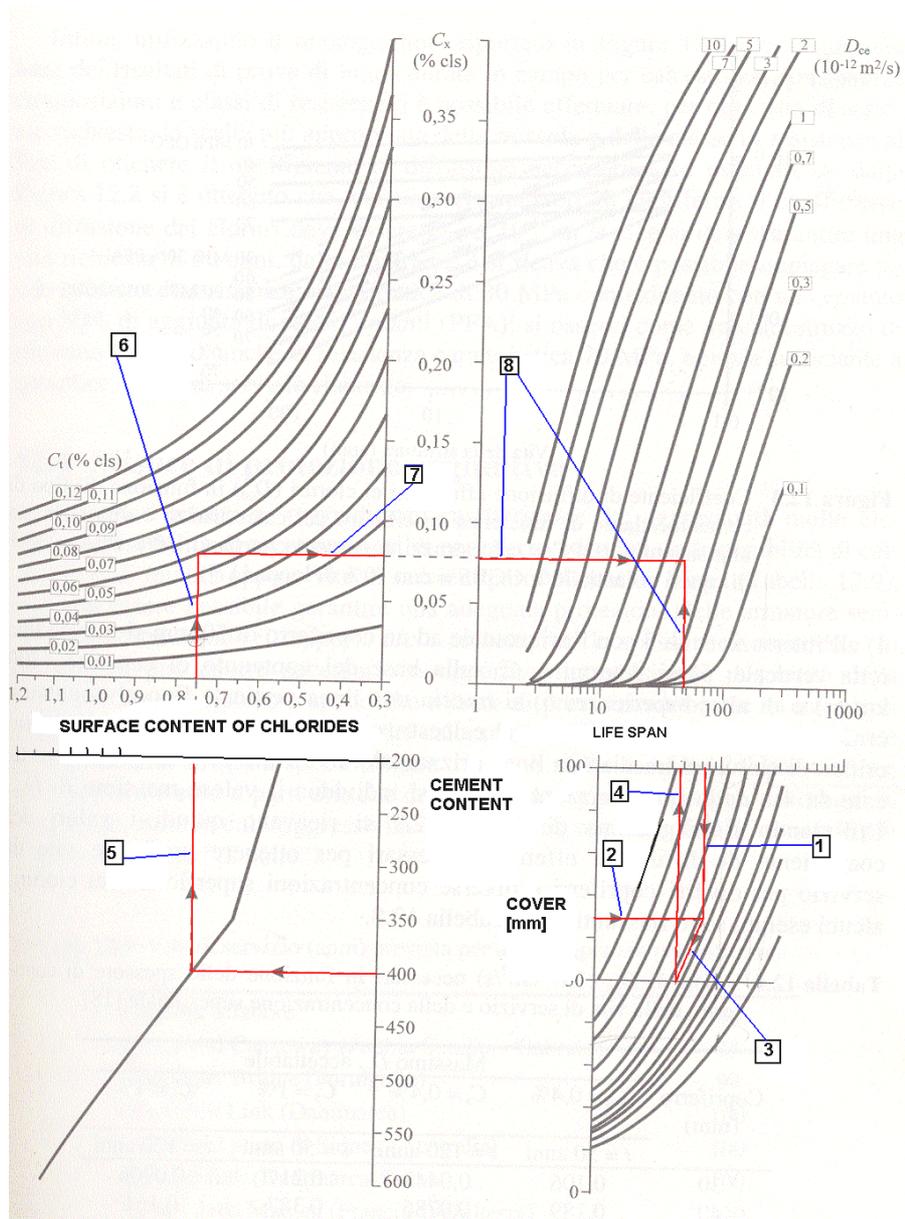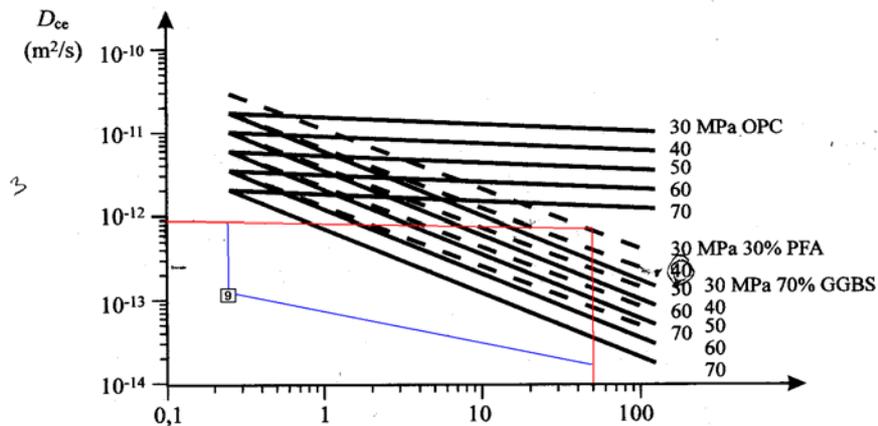
**Figure 5:Bamforth graph 1**

9. Now, using the second chart it is possible to find the concrete that has to be used in order to provide the $D_{ce}$ and the design life required

## 5   CONCLUSIONS

As this paper explained there are several different effects that can degradate a reinforced concrete structure and, probably, one of the most important is the corrosion of the rbars. Even if this phenomenon involves difficult chemical and electro-chemical equation, engineers developed sinple methods to assess the damage of a structure caused by the corrosion of the rebars. As explained in the previous paragraph, in fact, it is possible to design a durable structure with respect to corrosion by using simple equations and by using standard graphs. These methods are based almost entirely on empirical parameters but their results are in good accordance with the observations.
The only thing that has not been developped yet is a comprhensive method that can assess the effect of the single degradation causes and of their interactions.

**References:**
**[1]**   P.Pedeferri, L.Bartolini: La durabilita' del calcestruzzo armato. McGraw-Hill (2000)
**[2]** C.L.Page,: *Nature and Properties of Concrete in Relation to Reinforcement Corrosion*. (1992)
**[3]** *Corrosion in concrete-Monitoring, Surveying And Control by Cathodic Protection.*GCC seminar on corrosion, London(13th May 1996)
**[4]** C.L.Page, K.W.J Treadaway, P.B. Bamforth: *Corrosion of reinforcement in Concrete.* Society of chemical Industry (1990)
**[5]**A.P. Crane: *Corrosion of reinforcement in Concrete Construction*. Society of Chemical Industry (1983)
**[6]**J.L. Dawson,*Corrosion Monitoring of steel in Concrete.* Society of Chemical Industry (1983)