

PROBABILISTIC TREATMENT OF REBAR DEPASSIVATION AND ITS INFLUENCE IN THE CALCULATION OF STRUCTURAL LIMIT STATES

C. ANDRADE*, F. TAVARES*, J. FULLEA*, AND D. IZQUIERDO*.

*Center for the Durability and Safety of Structures and Materials,
CISDEM, CSIC-UPM
C/ Serrano Galvache nº4, 28033, Madrid, Spain
Corresponding author: C. Andrade, e-mail: andrade@ietcc.csic.es

Key words: reinforcement corrosion, service life, chloride threshold, corrosion probability, limits states.

Abstract: Chloride threshold for reinforcement corrosion has been found to be very variable in function of several material and environmental characteristics. Regarding carbonation, the corrosion onset is associated to the arrival to the rebar of the carbonation front. In both cases it is usually neglected in the calculations the geometrical fact of considering the whole perimeter of the rebar. Regarding the corrosion propagation, the evolution can be modelled in function of the concrete resistivity which based in concrete water saturation gives the corrosion rate. Variation of the nominal values of the diffusion coefficient of chlorides and carbon dioxide, of the chloride threshold and of the corrosion rate make very uncertain the predictions. In present paper is presented an attempt to reduce the uncertainties but a more thorough analysis of the physical processes happening during chloride depassivation by integrating the initiation to the propagation period and calculating the probability of failure due to the arrival of a certain chloride threshold or the carbonation front. Then the progress of the corrosion is taken as the parameter to define the most technically suitable probability of depassivation. The corrosion rate developed is made a function of the diffusion coefficient and of the saturation degree through their relation to the concrete resistivity. An example is commented to illustrate the approach.

1 INTRODUCTION

Concrete structures may suffer deterioration by reinforcement corrosion, due to the contamination by chlorides or the ingress of carbon dioxide. This attack shortens the service life of the structures whose repair supposes high economical investments. On the other hand the advance on new concrete mixes types are promoting the design requirement of 100 years of service life for important structures. This specification is usually made by assuming that corrosion is not produced during this timeframe considering that the process is diffusion controlled and second Fick's law is going to be applied in the

calculations and by defining only a diffusion coefficient threshold. Although to specify a target service life and a mechanism of attack seems and advance there are problems in fulfilling the requirement because in both cases, chlorides and carbonation, the solution of the diffusion law is not exact because the initial and boundary conditions are not fulfilled due to either the surface concentration, the diffusion coefficient or the concrete moisture are not constant along the structure's life^[1, 2].

Another key aspect of the calculation of service life in chloride bearing environments is the selection of a chloride threshold; Cl_{th} which is not a fixed value. These variable

conditions make the calculations very uncertain, preventing to advance in the durability design, in particular in finding a quantitative definition for a “corrosion limit state”. In present paper are analyzed the key aspects to be specified in service life models, in particular the corrosion onset and how to link this “limit state of corrosion” to the classical verification of the serviceability and ultimate limit states (SLS & ULS).

2 INITIATION PERIOD

In the case of carbonation, in general “moving boundary” conditions are considered for the calculation of the time to corrosion initiation, while in the case of chlorides the ingress is visualized by showing a decreasing chloride concentration profile. The typical solutions of the differential diffusion equation aim into the “square root law” for carbonation (expression 1) and of the “error function” (expression 2) for chloride attack, assuming in both cases that the external concentration is constant.

$$x_n = V_{CO_2} \cdot \sqrt{t} \quad (1)$$

$$\frac{C_s - C_0}{C_{th} - C_0} = \left(\frac{x}{2\sqrt{D_{ap} \cdot t}} \right) \quad (2)$$

However, in real atmospheres this constancy may not be operating in the case of chloride attack (the different concretes show different surface concentration which evolve with time), while in the case of carbonation what usually is variable is the external humidity. Then, the conditions assumed to solve the differential diffusion equation, may not be fulfilled. To solve this difficulty of variable external conditions numerical analysis can be used. Another possibility that gives only approximate solutions consists in introducing mathematical modifications in equations 1 and 2 which on the other hand, depart from the rigorous solution.

In any case, it is completely insufficient to specify only the D_{ap} because a variation of the rest of parameters may give results of service life with decades of difference. Taken the chloride penetration as example, the parameters to be defined with that of the diffusion coefficient, D_{ap} , are: a) the surface chloride concentration, C_s , if expressed as total chloride concentration and its increasing with time b) the aging factor, n of the diffusion coefficient and how long it is produced and c) the chloride threshold, C_{th} .

Regarding *the* C_s , when expressed in terms of total chloride concentration, it increases with time until a certain maximum due to the chloride binding. Figure 1 shows and example of concretes blocks placed in a beach in the tidal zone

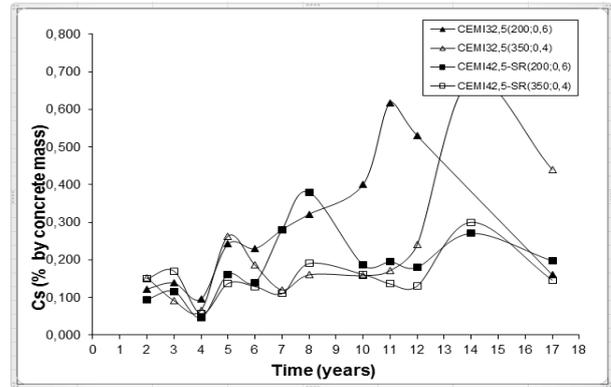


Fig. 1: Increase of C_s with age in real sea water exposure.

This evolution of C_s with time has the consequence to influence the value of the calculated D_{ap} for the fixed cover depth where the bar is located

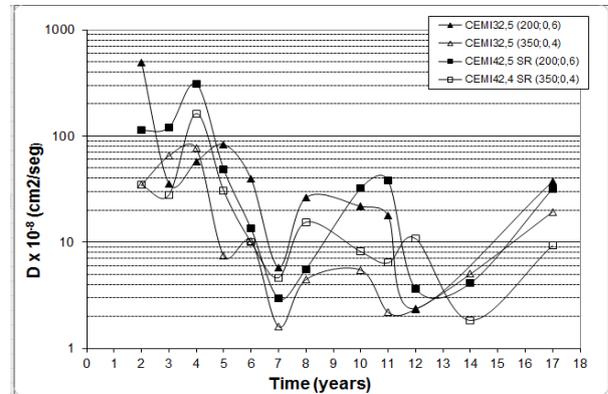


Fig. 2: Variation of D_{ap} with age and C_s .

Thus, as indicated in figure 2 the diffusion coefficient increases when the surface concentration decreases. This aims in which is shown in figure 3 that for the same D_{ap} at a fixed time, the chloride concentration at the bar surface is higher as the Surface concentration is.

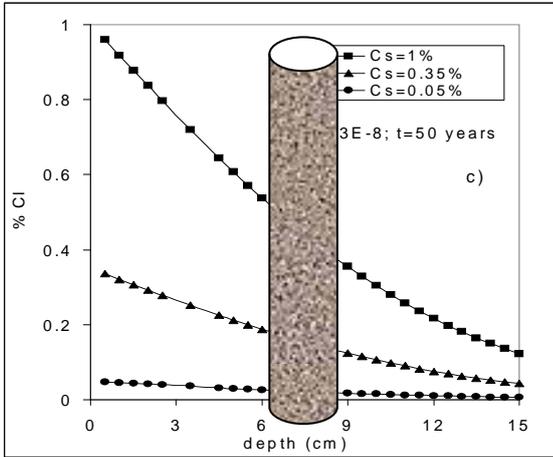


Fig. 3: For the same diffusion coefficient, a higher surface concentration means a higher chloride concentration at the rebar level.

There are two ways to solve this difficulty of the dependence of the calculated D_{ap} value with the C_s one: 1) by introducing in the calculation the law of C_s increase with time and its statistical variation and 2) by considering in the calculation only the water soluble chlorides. Several laws of evolution of the surface concentration have been proposed, but it seems a more accurate manner, the use of water soluble chloride concentrations in the pore solution in the chloride profile, as the C_s in the first concrete superficial mm can be calculated from the external chloride concentration multiplied by the concrete porosity.

With respect to the aging factor it appears from the evolution of the microstructure which makes to decrease the D_{ap} with time. This evolution is the result of the hydration progression and of the chloride binding with time itself, which aims into a decrease of the porosity and a slower chloride penetration. Two are the questions to be solved for the prediction of the service life: which is the slope of attenuation of the D_{ap} and when the process stops.

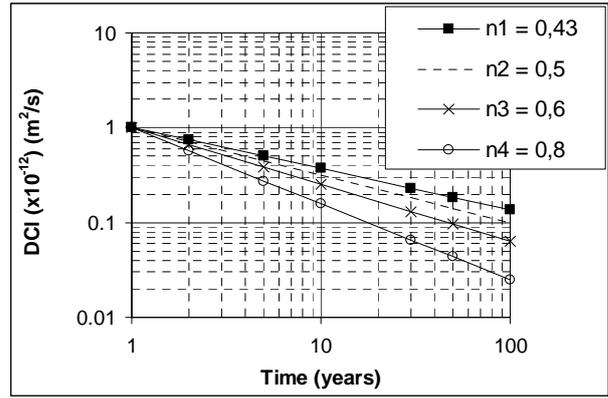


Fig. 4: a) effect of exponent n on the decrease of D_{ap} with time assuming $t_0=1$ year: evolution of the log of the inverse of resistivity with time. A final remark that has to be taken into account is that the time at which the t_0 is considered influences the extrapolation.

The impact of the value of the aging factor or slope of decrease of D_{ap} is shown in figure 4 which indicates that the drop can be very significant aiming into one or more orders of magnitude in the predicted life time. One possibility would be the measurement of the D_{ap} at two or more ages, which on the other hand results more expensive. The other possibility is to monitor the electrical resistivity, ρ , [3] based in its inverse relation to the diffusivity. Being the ρ a NDT method, it enables consecutive measurements in the same specimen. The relation between the aging factor n of the D_{ap} and that of the resistivity q is: $q = 0.8 n$. Figure 5 shows the representation of the inverse of the ρ with time in a particular case where only three measurements with time were made.

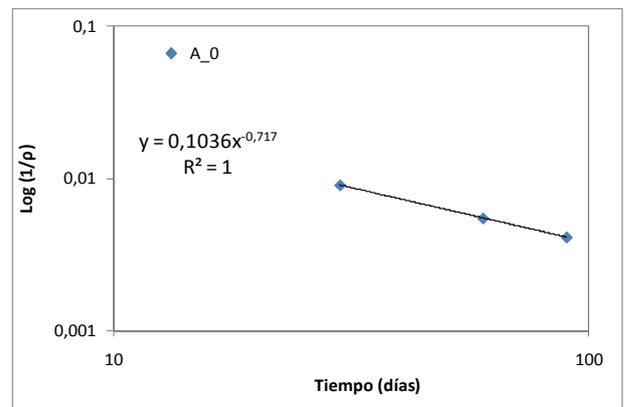


Fig. 5: Evolution of the inverse of the resistivity similar to that of the D_{ap} .

The other important aspect that may influence the prediction is the *test type* and the *time* at which to perform the experiments. The tests can be based in natural diffusion or performed by accelerating the process by migration. The comparison of natural and accelerated tests may not agree and therefore the use of a value or another may mean a different prediction.

In order to take into account these variations one possibility is to consider a statistical distribution in the C_s and in the D_{ap} . An example of the calculation of the probability of a certain chloride concentration to reach a certain cover depth at a certain time is given in figure 6. It illustrates the feasibility to use probabilistic treatments to study the impact of different parameters in the predicted service life.

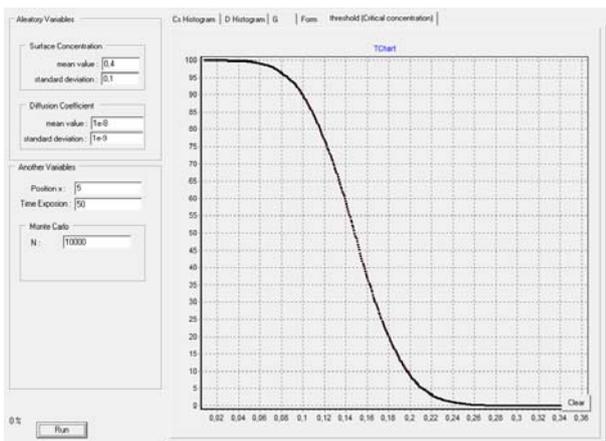


Fig. 6: For 50 years of service life the graph shows the probability that the chloride concentration in the “x” axis reaches 5 cm of cover depth.

3 CHLORIDE THRESHOLD

In the case of chlorides, the general consideration is that the corrosion develops when the threshold value, Cl_{th} , reaches this position. However, analyzing the physical sequences of the event, the process is not just instantaneous due to the bar has a relatively big size with respect to the concrete cover. That is, the threshold reaches first the more external surface of the bar and in evolves reaching the rest of the perimeter as the time passes. Then the depassivation front progresses around the perimeter, as figure 7

shows, the developing of the corrosion onset is not an instantaneous event.

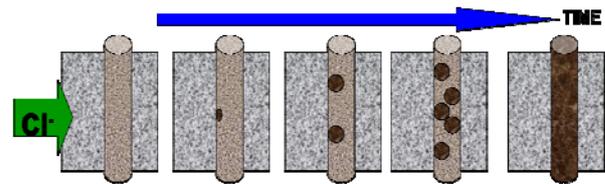


Fig. 7: Steps in the process of depassivation by a front reaching first the external bar surface.

Then, the definition of the corrosion onset from an engineering point of view cannot be linked to the first corrosion event. For the corrosion initiation definition, it is necessary also to think in statistical terms as the corrosion process is of stochastic nature in its probability of occurrence and in its geometrical distribution.

At this respect, in figure 8 are reproduced two statistical distributions [4, 5] of the probability of corrosion in function of the chloride concentration. That from Marqueset [4] is a lognormal distribution and was collected in real structures in Norway with a mean value of $0,77 \pm 0,24\%$ by cement weight while that of Izquierdo [5] is a normal distribution with a mean of $0,70 \pm 0,20$ and was built from laboratory results made on mortar specimens fabricated with different cement types and submitted to potentiostatic tests.

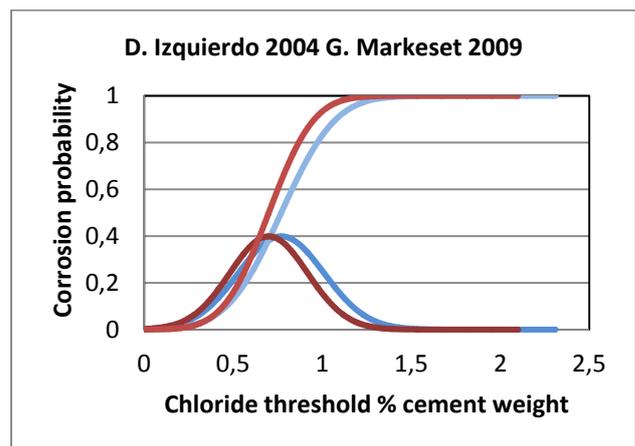


Fig. 8: Statistical distributions of the chloride threshold by Marqueset [4] (in blue color) collected in real structures and by Izquierdo et al [5] (in red color) made in laboratory conditions.

In spite of that both studies come from very different sources of data, they seem coherent from the point of view that in real conditions and real concrete, the amount of chloride needed for producing corrosion is a bit higher than in the laboratory conditions. The so close values of the mean and standard deviation values indicate the existence of a unique chloride threshold statistical distribution.

This statistical distribution of the chloride threshold can be combined with a full statistical treatment of the parameters of the equation 2 by assuming that not only the C_s and the D_{ap} are statistically distributed but also the C_{th} is. In figure 9 is shown an example made with a program using log-normal distribution for all parameters made by means of Montecarlo method. Assuming the values in the example of: $C_s = 2 \pm 0.1\%$, $D_{ap} = 1E-8 \pm 1E-9 \text{ cm}^2/\text{s}$, $C_{th} = 0.70 \pm 0.2\%$ and $x = 5 \pm 0,7 \text{ cm}$. The graph shows the probability of corrosion for the particular example indicating that it will be of 10% at 24 years and of 50% at 43 years. The failure probability at 50 years will be of 0.60%.

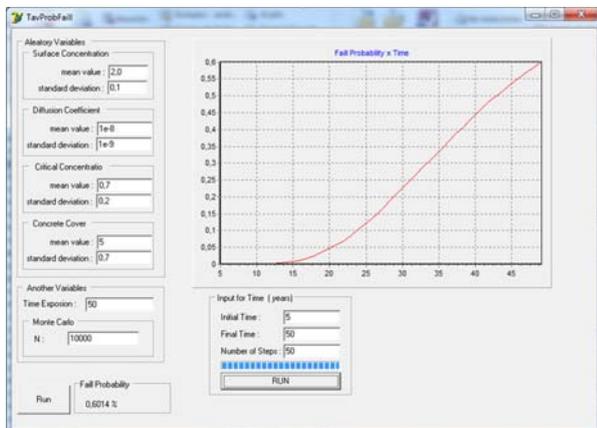


Fig. 9: Example of full statistical calculations of the corrosion probability in function of a particular concrete and chloride threshold distributions.

This statistical treatment facilitates to define an engineering C_{th} or corrosion onset in terms of the probability of corrosion, but which is the most appropriate probability? It has been recommended [6] a probability of 10% although Marqueset [4] and Gulikers [7] discuss this assumption, whose justification

has not been found beyond the general concept that a probability of 10% of occurrence is the usual range for serviceability limit states with β values around 1.3. How conservative or appropriate is this probability of the 10%? The only manner to respond is by analyzing the consequences of the corrosion produced by accounting for the accumulated corrosion at different steps.

4 LIMIT STATE OF CORROSION

For analyzing the consequences of the corrosion in the structural load-bearing capacity, the total bar section loss or accumulated corrosion P_{corr} has to be accounted as shown in figure 11. It shows that the loss in cross section will be progressing from the more external surface of the bar as the chloride threshold is advancing in depth.

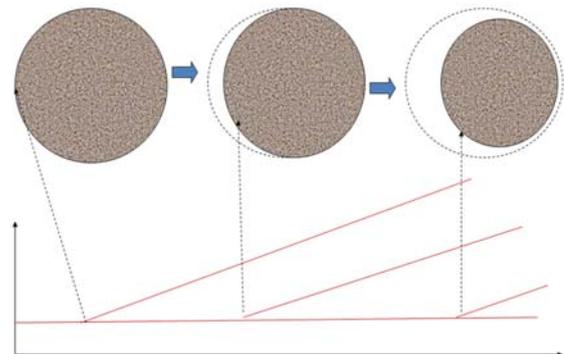


Fig.10: Evolution of the loss in cross section with the advance of the aggressive front

The different corrosion penetrations achieved will enable to calculate when cover cracks may appear, because a first crack can be produced with only $10 \mu\text{m}$ of P_{corr} [9] and how these cracks will evolve. Then the SLS may be exceeded before the front reaches the back part of the bar. Then the limit state will not be linked to a fixed probability of corrosion but it would depend on how critical from a structural point of view are the particular structural section in the sense that a SLS or ULS is exceeded.

The analysis of the accumulated corrosion produced helps to propose that it has to be the verification of the SLS and of the ULS which should be made for the sake of establishing the

maximum probability of corrosion allowed after depassivation for each particular structure. That is, it is through the calculation of the accumulated corrosion from the exterior part of the reinforcement and the corresponding general or localized loss of section that the acceptable probability of corrosion should be established, by verifying the several SLS and the ULS

5 CONCLUSIONS

In present paper the main achievements were:

1. It is given a unique statistical distribution of the chloride threshold,
2. From it, it has been calculated the probability of corrosion at the most external surface of the bar, and
3. From the calculation of P_{corr} it is possible to verify the impact of such corrosion penetration into the SLS (crack appearance and deflections for instance) or of the ULS.

6 ACKNOWLEDGEMENTS

The authors would like to acknowledge the financing of the Ministry of Science and Innovation for the INGENIO 2010-CONSOLIDER Project on “Safety and Durability of Structures: SEDUREC”.

7 REFERENCES

- [1] Bamforth, P., Chapman-Andrews, J. 1994, International Conference on Corrosion and Corrosion Protection of Steel in Concrete, Sheffield Academic Press, Ed. N. Swamy Ed., pp. 139-156.
- [2] Andrade, C., J. L. Sagrera, et al. (2000). 2nd International Rilem Workshop on Testing and Modelling the Chloride Ingress into Concrete 19: 121-134.
- [3] C. Andrade, M. Castellote and R. d’Andrea- Journal of Nuclear Materials 412(2011) 209-216.
- [4] G. Markeset. Materials and Corrosion, (2009), 60, n8, pp 593-596.
- [5] Izquierdo, D., Alonso C., Andrade C., Castellote M. (2004). *Electrochimica Acta* 49(17-18): 2731-2739.
- [6] *fib* Bulletin no. 34- “Model code for service life design” (2006)
- [7] J. Gulikers. 2006, A. Proceedings of the RILEM International Workshop on “Performance based evaluation and indicators for concrete durability” Madrid-Spain, pp 165-176.
- [8] Andrade, C., J. Fullea, et al. (2000). Measurement and Interpretation of the on-Site Corrosion Rate. Rilem Proceedings no. 18: 157-165.
- [9] C. Andrade, F. Tavares, M. Prieto, P.Tanner and D. Izquierdo RILEM Week 2011- “Advances in Construction Materials through Science and Engineering” 5-7 September- Hong Kong.