Corrosion rate values in real structures and their statistical distribution

Carmen Andrade
Visiting Research Prof. International Center for Numerical Methods in Engineering (CIMNE), Madrid, Spain

David Izquierdo
Lecturer, Polytechnical University (UPM) of Madrid, Spain

ABSTRACT: When the reinforcement corrodes, the corrosion rate values do not remain constant because of the intrinsic variability of the concrete as composite material, to its aging with time and due to the changes in the external environmental conditions. In present communication results recorded in several real structures are organized as a single statistical distribution separating the carbonated to the chloride contaminated structures. Additionally, evolution of corrosion rate with time of specimens contaminated with chlorides exposed to natural conditions are reported. Comments are made on the spatial and temporal variability of the corrosion rate in real exposure conditions.

INTRODUCTION

The alkalinity of the hydrated cement induces the passivity of the steel which does not corrode indefinitely if the conditions are maintained. Passivity is understood as negligeable corrosion, which in electrochemical terms means that the measured values of the corrosion rate are below 1-2 µm/year (1). When corrosion develops there may be increases of these values of one or two orders of magnitude depending on the conditions of the concrete. Ranges of expected corrosion rates in laboratory or real structures were established in a Rilem recommendation (2). After corrosion starts, in addition to the intrinsic variability of concrete as composite material, the instantaneous corrosion rate evolves with concrete aging and with the external environmental changes. This permanent evolution makes necessary its statistical characterization for its use in structural modelling.

The systematic and statistical treatment of concrete properties in real structures has been only made for the strength or less values have been collected on temperature (3). Very scarce or nil are on concrete durability parameters. Thus, few references are found on parameters as the degree of saturation or the corrosion levels [4]. On the chloride ingress are however remarkable the work made in Norway on the chloride threshold (5) that have been mentioned by the *fib* in the MC2010 (6).

The research group of the authors of present communication have recorded data (7) during more than thirty years on specimens exposed to the atmosphere. These data are here statistically preliminary treated following a recent publication on the intrinsic spatial variation (8) of the corrosion rate and the resistivity.

EXPERIMENTAL

The corrosion rate values shown in this paper were obtained with a portable corrosion-meter with modulated confinement of the current (9) for delimiting the area of the bar that is polarized. The equipment uses the Polarization Resistance (R_p) technique following (10). Thus, the R_p and I_{corr} are obtained from the equations:

$$R_p = [\left(\frac{\Delta E}{\Delta i}\right)_{\Delta E \to 0} - R_{oh}] \quad (1)$$

$$I_{corr} = \frac{B}{R_{p,ef}} \quad (2)$$

Where ΔI is the galvanostatic pulse applied, ΔE is the shift in potential produced, R_{oh} is the ohmic drop produced by the concrete, B es a constant with an averaged value of 26 mV and $R_{p,ef}$ is the value of the "effective" Polarization resistance (the R_p multiplied by the polarized area). The units are: R_p [Kohm], $R_{p,ef}$ [Kohm·cm^2] and I_{corr} [μA/cm^2].

For the interpretation of the statistics, it is underlined that:

- The values were collected in the inspections made to assess the condition of existing structures suffering corrosion, either by carbonation or chloride attack. They represent then not all the population of structures, but that part (around 15% was found in previous studies (9)) with visual signs of corrosion.

- The measurements were made in each structure on the same or consecutive days, that is, with almost the same external environmental conditions.

- In each structure, the selection of measurement zones was made by choosing only one zone were corrosion is likely not yet produced and several zones were the corrosion was evident. Then, the number of places measured with no corrosion are smaller than those corroding, although. Additionally, some apparently corroding have shown values below the limit of 1-2 μm/year. That is, the values in each structure represent a kind of spatial variation not only of the material, but also of different exposure classes (humidity and contamination) and types of concrete if it varies in the differnt elements of teh structure.

RESULTS

Variation in the same structure (spatial)

Figure 1 shows the averaged corrosion rates values measured in structures contaminated by chlorides (either due to deicing salts –bridges- or by marine environments) and figure 2 those of their coefficient of variation (CoV). Figure 3 shows rhe values recorded in carbonated structures and figura 4 their CoV.
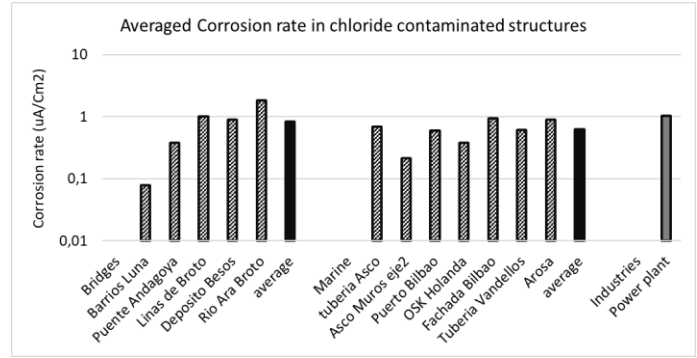

Figure 1: Average values of corrosion rate in different structures contaminated by chlorides
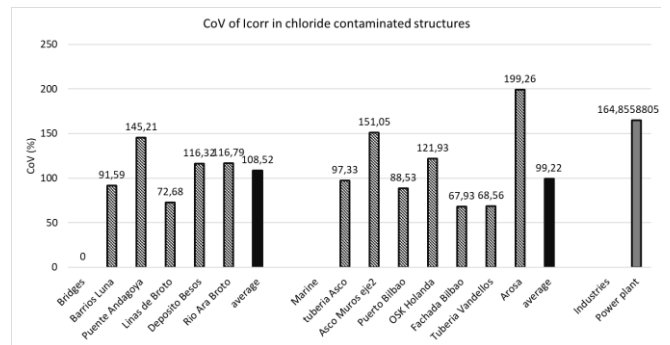

Figure 2: Coefficient of variation (spatial variation) of the structures of figure 1for chloride contaminated structures.
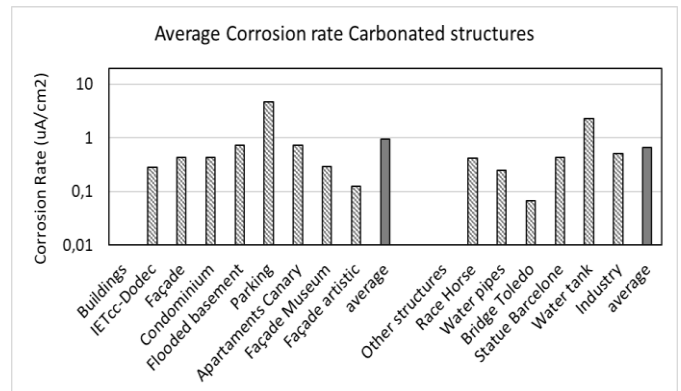

Figure 3: Average values of corrosion rate in different carbonated structures.
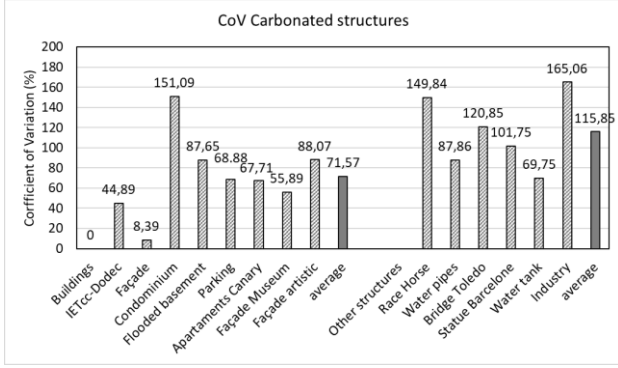
Figure 4: Coefficient of variation (spatial variation) of the structures of figure 3 for carbonated structures.

The representation of all these data statistically ends in figure 5, where it is apparent that carbonated or chloride contaminated concrete give almost exactly the same statistical distribution resulting in a log-normal distribution whose characteristics are given in Table 2. However, the average value and the CoV are larger in the case of structures contaminated by chlorides. The coefficient of variation is large because in the same structure there are non corroding zones and other with high corrosion rates. The probability of finding values of corrosion rates above 10 $\mu A/cm^2$ is lower than the 0.35% and values above 5 $\mu A/cm^2$ smaller than the 1.5%.
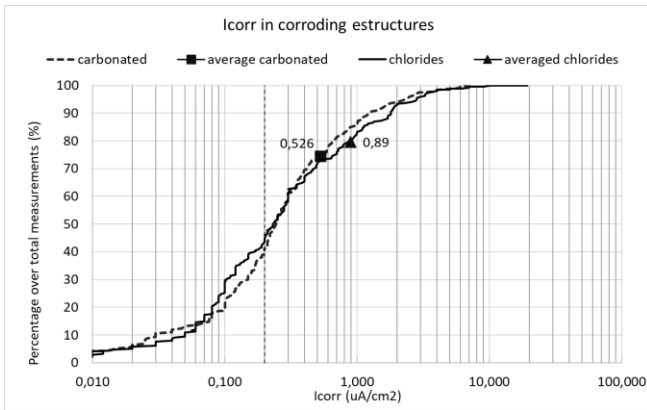

Figure 5: Proposed general statistical distributions of corrosion rate values in corroding structures

In the figure 5 is underlined in vertical with a dashed line the limit of $0.2\mu A/cm^2$ which could be taken as the frontier between active and negligeable corrosion. The value of probability for this limit in corrosion rate results around 45%, which means that is proportion of the measurements made in a corroding structure would show negligeable corrosion.

Table 2: Characteristics of the statistical distribution of averaged corrosion rate values and their coefficient of variation in real structures.

Type of contamination	Probability	Averaged corrosion rate $\mu A/cm^2$	Coefficient of variation
carbonation	75%	0.526	177.30 %
chlorides	80%	0.89	221.86 %

Variation during time (temporal)

In figure 6 is shown an example of the temporal variation of the corrosion rate and the figure 7 of the temperature and relative humidity inside the concrete near the bar of a specimen with 3% calcium chloride admixed, exposed outoors non protected from rain. The variation of temperature together with the rain periods induce the changes of the detected RH values in a hole inside the concrete and consequently, the corrosion rate I_{corr} changes (1,7).

Considering the period of 4 years shown in the figure 6 and 7, the figure 8 shows the CoV of these variables during this period. The variation of the corrosion rate is much larger and above 100% during the period, which si attrributed to the corrosion rate changes with logarithmic shifts. In this case the CoV of the corrosion rate can be derived from the following simple relation:

$$CoV\,(I_{corr}) = 6 \cdot (CoV - RH) \qquad or$$
$$= 2.4 \cdot (CoV - Temperature) \;\;(3)$$

These relations are only examples of the type of data that are needed in order to be able to predict the behaviour from a particular climate.
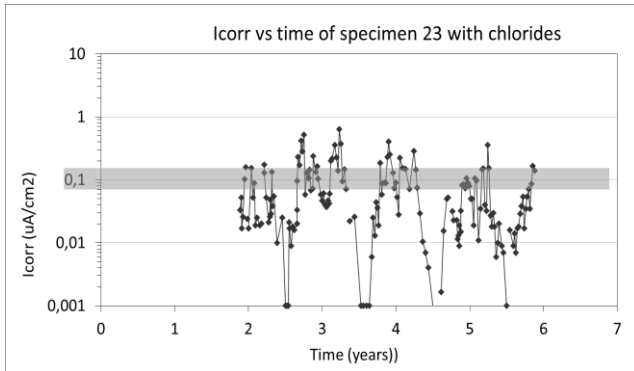

Figure 6: Evolution of the corrosion rate, in a specimen exposed outdoor non-sheltered form rain with 3% calcium chloride admixed.
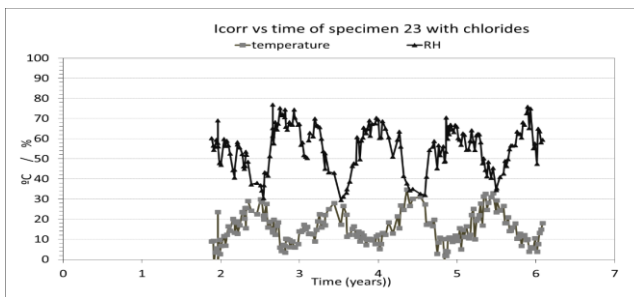

Figure 7: Evolution of the temperature and the Relative Humidity in a specimen exposed outdoor non-sheltered form rain with 3% calcium chloride admixed.
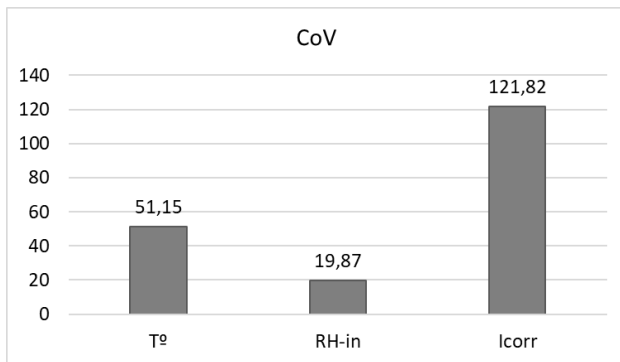

Figure 8: Coefficient of variation of the parameters shown in figure 7 during teh epriod considered.

DISCUSSION

The statistical treatment of the corrosion rate values made here are the preliminary steps for a rigorous statistical treatment is established. Much more work will be needed to produce a tool that could be used by designers. However, the treatment made here enables the framework to be proposed. Thus, the corrosion rate may vary largely due to the typical evolution of the climatic events: day and night and the seasonal ones. Then it seems that an annual average could be a reference period suitable for prediction providing the safety calculations are accounted annually and that the seasons are repeated and therefore, the annual average value is almost constant as can be deduced from figures 9 and 10 (in this last case as the corrosion rate is below 0.1 µA/cm^2 the value can be considered as negligeable corrosion the whole period)
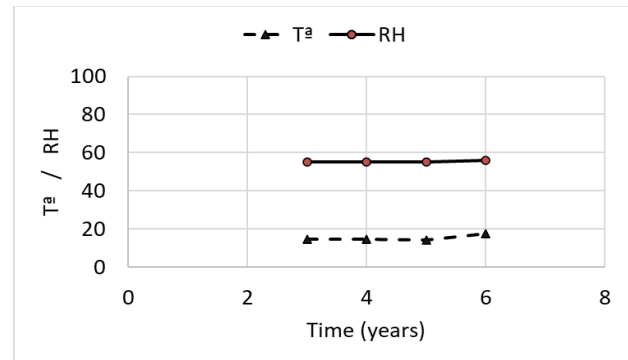

Figure 9: Mean values of the temperature and relative humidity of the values shown in figure 7.
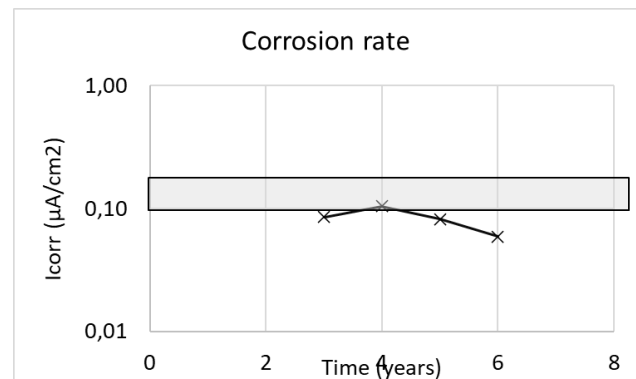

Figure 10: Mean values of the corrosion rates shown in figure 6

A final comment on these low values of the corrosion rate in a chloride contaminated specimen is that they can be explained due to the dryness of the climate in Madrid which, as deduced from figure 6, induces values above the limit of 0.1-0.2 $\mu A/cm^2$ very short period along the year making so low the annual average value in spite of the chloride contamination.

CONCLUSIONS

Data of corrosion rate were collected in real site corroding structures and represented as the probabiity of corrosion rate. The measurements made in the non corroding zones are fewer than the number of measurements in the corroding zones.

- The spatial variation is very much dependent on the contamination and humidity distribution in each element and in the whole structure. In its interprtation it has to be taken into account the number of data measured in the corroding and non corroding zones.
- The varation found depends not only of the spatial variation, but also of the temporal evolution produced by the climatic seasons in the sense that the values can change depending on the season where the measurement is made.
- The temporal variation is influenced by the regime of raining and tenperature due to the climatic conditions.
- For the whole population of structures measured (spatila valation) it was found an averaged value of 0.526 $\mu A/cm^2$ for the carbonated structures and of 0.89 $\mu A/cm^2$ for those containing chlorides. Their Cov were around 70-200% in the chloride contaminated structures and 8-165% in the carbonated cases.
- With respect to teh temporal variation, In present data, the CoV is larger in the corrosion rate than in the RH or in the temperature, but this is due to the corrosion rate may vary more than one order of magnitude for small variations of humidity or temperature as deduced from figure 6.

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