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Hormigón y Acero, 2025
https://doi.org/10.33586/hya.2025.4133

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DOI: https://doi.org/10.33586/hya.2025.4133

Para ser publicado en: *Hormigón y Acero*

Por favor, el presente artículo debe ser citado así:
Andrade, C. (2025) Why the Impact of Climatic Change on Reinforcement Corrosion Cannot Be Predicted at Present, *Hormigón y acero,* https://doi.org/10.33586/hya.2025.4133

WHY THE IMPACT OF CLIMATIC CHANGE ON REINFORCEMENT CORROSION CANNOT BE PREDICTED AT PRESENT

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Abstract

Climate change calls into question the durability of infrastructures when environmental actions exceed those foreseen for their design. In the case of reinforcement corrosion, the main corrosion control parameter is the evaporable water content (retained water) of the concrete. Despite its importance that also affects other deterioration processes, data on its content in full-scale structures are scarce, in contrast to the numerous published references on laboratory experiments. This article presents values of the degree of saturation of specimens exposed to the weather and their impact on the corrosion potential, the resistivity of the concrete and the values of the corrosion rate. It can be deduced that the external conditions of temperature and RH are not the controlling factors of the corrosion process, but mainly rainfall. The results show that the only biunivocal relationship with the corrosion rate is that of resistivity, but a "function" has not yet been established that characterizes the environment to deduce its effects on the water content of the concrete and therefore on its resistivity. This lack of correlation of corrosion with the temperature and relative humidity outside calls into question the work published so far on the impact of climate change on infrastructures, since they are based on these external parameters and not on the water retained inside the concrete.

Keywords : climate, corrosion, concrete, relative humidity, temperature, rain.

INTRODUCTION

The classification of the exposure classes in present standards recognises the impact that the different environments have in the concrete durability, either on the concrete itself or onto the reinforcements [1]. This classification for preventing steel corrosion attends first to whether the concrete is carbonated or is chloride contaminated and, in the case of carbonation, it distinguishes the risk as a function of the water saturation. In the case of chloride attack, the main distinction is related to the possible chloride level, but chloride penetration depends on the degree of concrete saturation as well. In cases of other deterioration mechanisms as sulphate, or frost attack, or alkali-aggregate reaction, they also need a certain level of moisture to develop. Then, the concrete water content is the main factor for accelerating the deterioration processes, for steel corrosion as for concrete deterioration. That is, the degree of water saturation [2,3] or better named “water retention curve” is the controlling parameter for any prediction of the impact of climate in the concrete durability.

At present, such relationship ~~has~~ not been established because the difficulty to account for the water retained into the concrete, It can be measured: a) or by weighing (before and after a certain weather event), weight not feasible in a large structure or b) can be indirectly measured through the changes in concrete resistivity, but previous calibration is needed on the relation of the resistivity of a particular concrete and its water retained curve. Without the weight data it is not possible to predict the relation between the climatic events and the level of concrete water ~~saturation~~. This was the main aim of a work undertaken around 20 years ago [2,3] planned to collect data on the several corrosion parameters as a function of the external climate.

In spite of the scarce data on weight variation with climatic events, there are an increasing number of studies claiming to predict the impact of the climate on concrete durability [4-11], based only in the increase in temperature and if this increase will accelerate the deterioration processes, or by considering only the external RH. It is of particular concern some reports [7,8] with these wrong assumptions. These studies are based on theoretical models not long term calibrated and with arbitrary or assumed input parameters. In the work mentioned [2,3] was noticed that an increase of temperature may lead through water evaporation into less internal humidity, in addition to emphasize that internal RH and external ones may significantly differ. These counter effects with the increase in temperature, were not considered in [4-10] calculations.

The water saturation in a concrete exposed to the atmosphere and rain after the period of drying after curing is the result of reaching an equilibrium with its surroundings, that depends on temperature, relative humidity, but mainly on the rain/snow regimes [2,3], and also on the possible use of de-icing salts, that are hygroscopic. At present there is not a mathematical function linking the external climate parameters with the concrete water content (water retention curve) and therefore, the prediction of any climatic change is unfeasible.

In the particular case of carbonation, the process is dependent on the internal relative humidity (RH), presenting a maximum carbonation rate in intermediate values (around 60%), below or above which, the rate of carbonation decreases significantly. However, the internal RH is different ~~than~~ from the external one, sometimes is ~~the~~ double [2,3] because of the temperature and hysteresis effects. The predictions based on the external RH will lead to fully erroneous conclusions.

As an example of the complexity of the interaction of climatic events and ~~the~~ concrete [12], when it rains concrete absorbing water during the duration of the raining period depends on previous concrete internal relative humidity and on the temperature. Of the water absorbed, a part will evaporate depending on the external relative humidity and on the temperature, that may be different than during the rains. Absorption of water and evaporation cycle has hysteresis because the different speed in absorption-evaporation, which makes multiparametric the dependence with the climate of the annual water retention curve in a particular concrete. The water retention curve depends certainly on the temperature, but in a complex manner and then, the possible mathematical expression relating external climate and internal water retention also is complex and needs careful consideration of all the processes involved.

Works were undertaken around 35 years ago [2,3] advancing the understanding of the complex relation between environment and local climate by exposing concrete specimens outdoors and measuring the climatic events simultaneously with specimen weight and the corrosion parameters. In this paper results are given that were results collected in the specimens during more than 23 years. This long period already serves to deduce some general trends. Results of a carbonated specimens that serves to illustrate the general trends are shown for the whole testing period, and comparison between different specimens, in different exposure conditions, is made for a shorter period.

EXPERIMENTAL PROCEDURES

Specimens tested were of cylindrical shape (figure 1) [2,3] with an embedded central bar. Their size is of 7.5cm x 15cm that tries to reproduce a cover depth of around 3 cm thick, not to low and not too high for having an averaged value of the possible hysteresis in the response to the weather change.

They were fabricated with ordinary portland cement in the proportions shown in table 1. The table also indicates the exposure conditions of each specimen from 1999 when they were 5 years old. After their manufacturing the specimens were cured during 3 days under water and later, they were further dried until 28 days. Those containing chlorides added in the mix were introduced in a chamber at fixed RH/T regimes, while those non containing chlorides were carbonated at 100% CO_2 concentration until the weight was constant. When these specimens were fully carbonated, they were also introduced in chambers with fixed RH/T until they were around 5 years old (see Table 2).

Table 1 Mix proportions, label, porosity (after 28 days of curing) and exposure conditions of the specimens considered in present paper.

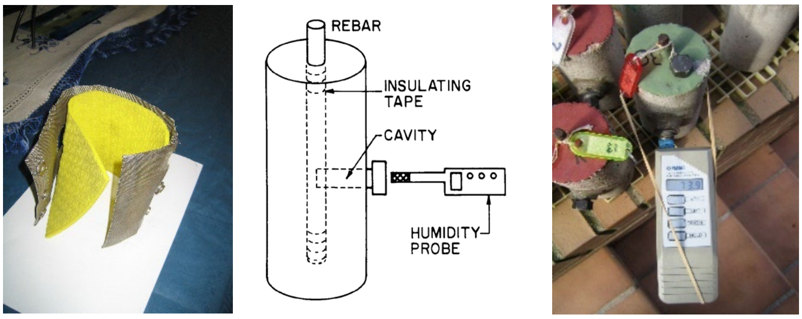
Mix proportions	**label**	**w/c ratio**	**Porosity (% volume)**	**Preliminary Condition**	**Exposure condition after 5 years old**
350kg cement/m^3	No. 2	0.5	5.7	carbonated	Exposed to rain
350kg cement/m^3	No. 4	0.5	5.29	carbonated	Protected from rain
250kg cement/m^3	No.13	0.5	7.6	carbonated	Exposed to rain
300 kg cement	No.23	0.6	12.44	3% $CaCL_2$ in the mixing	Exposed to rain

On the humidity/temperature regimes that the specimens were submitted to, they are summarized in Table 2. The first years they were submitted to several laboratory conditions at fixed temperatures, T, and relative humidity, RH until they were 5 years old. After this period, some of the specimens were exposed outdoors to natural atmosphere in Madrid-Spain. Madrid has a climate with relatively well marked seasons. It has a dry atmosphere which reaches values between 10-30% RH-IN during the summer when it seldom rains. Autumn and spring may be relatively mild (average temperatures of 14-15ºC and average RH between 60-65%). There are intermittent rain periods during the year, with an average precipitation of around 420 mm/year (figure 1 c).

a) Aspect of the specimen

b) Weighing

c) Pluviometer



d) Counter-electrode and sponge

e) scheme of the specimen and of the hole

f) Probe measuring internal RH and T

Figure 1 Several features of the cylindrical specimens used for the testing

Table 2-Regimes of humidity/ temperature

Time	28 days	Until 60 days life	Until almost 5 years life	Until almost 7 years life	From January1999 Until the end of the test
Action	Fabrication and curing	Carbonated: drying and carbonation Chlorides: exposure to fixed humidity and T chambers	Fixed RH/T in chambers	Outdoor exposure combined with several artificial wet-dry cycles	outdoor exposure in two different places more or less exposed to rain

The weather conditions near the exposure site of the specimens were monitored by means of the same Vaisala hygrometric probe (RH and T) (figure 1e and 1f) used for measuring the internal RH. For these conditions inside the concrete, the probe was introduced in the cavity shown in figure 1e for a certain time [13]. This cavity was made by removing the concrete and inserting a metallic tube of t~~he~~ depth reaching the bar position but without metallic contact to it and having a plug. Following (13) this creates a small chamber whose air is in equilibrium to the internal concrete moisture content and that was assumed to represent the RH/T-INT. Rainfalls were measured through a simple pluviometer (figure 1c).

To monitor the water content of the concretes, the specimens were weighed, as shown in figure 1b, each time the corrosion parameters were measured. The water volumetric fraction is calculated from the weight taking as « dry » value obtained after the long dry period of Madrid summer (from July to September), with usually induced RH-INT of around 30%. The degree of saturation is calculated with respect to the total empty porosity, that was measured by Mercury porosimetry after 28 days wet curing.

Corrosion techniques

The corrosion parameters measured were:

- the corrosion potential (E_{corr}), using as reference a saturated Ag/AgCl electrode
- the corrosion rate (I_{corr}) using the Polarization Resistance (R_p) method. The equation for calculating the corrosion current was [2,3,14]:

$$I_{corr}\ (\frac{\mu A}{cm^2})=\frac{26}{\left(\frac{\Delta E}{\Delta I}\right)_{Rp}=\left(\frac{\Delta E}{\Delta I}\right)_{exp}-R_{oh}} \qquad (1)$$

  Where the R_{oh} is the ohmic drop obtained in the recording of the current along testing time, that has to be discounted (as indicated in the denominator of equation (1) from the total value named “exp”.

- the resistivity (ρ) is obtained from the ohmic drop R_{oh}, directly given by the corrosion rate meter, which was a handmade portable potentiostat (figure 2-left) and more recently through the GECOR10 (figure 2-right). Figure 2 shows the specimen as well surrounded by the counter electrode in horizontal position to place the reference electrode in a small hole of the counter-electrode having a wet sponge (figure 1d) in between the specimen and this counter-electrode. To obtain the resistivity from the ohmic drop given by the potentiostat a “geometrical factor” was applied (15).

The basis of the polarization resistance technique to measure the corrosion rate parameters are given in a Rilem Recommendation [14]. The calculation of the penetration depth (P_{corr}) is made through the integration of the evolution of the instantaneous corrosion rate with the time as also explained in this Recommendation.

- $P_{corr} = 11.6 \cdot \int_0^t I_{corr}(t)[dt$ (2)

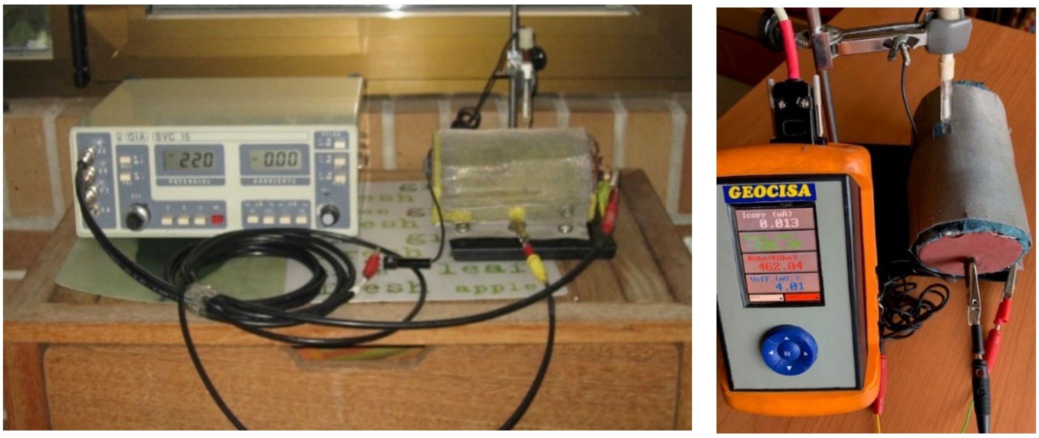


Figure 2 Left: Hand-made portable potentiostat used during the first 20 years of testing period and specimen with the reference, counter and the plug to the bar as working electrode. Right: GECOR 10 corrosion-rate meter used in the most recent period.

RESULTS

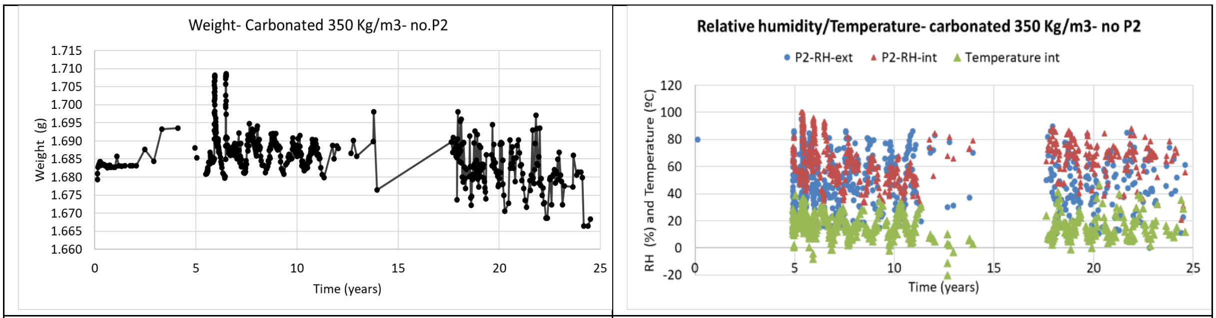
As a general illustration, first it will be given (figure 3) ~~the~~ several parameters measured during the whole life of specimen no. 2 (see table 1-350kg/m^3 of cement and carbonated) while later, a particular period for 4 years was selected to illustrate more in detail the performance observed. This period of four years was selected to have a balanced number of data, because as being the measurements not from sensors, but from individual measurements, their representativeness depends on their periodicity or on whether the measurement is made during the day or the night. A lot of care has been taken when analysing the data to avoid bias if the regime of measurements is irregular.

Specimen carbonated with 350 kg/m3 cement during the whole testing period of 23 years

Weight evolution

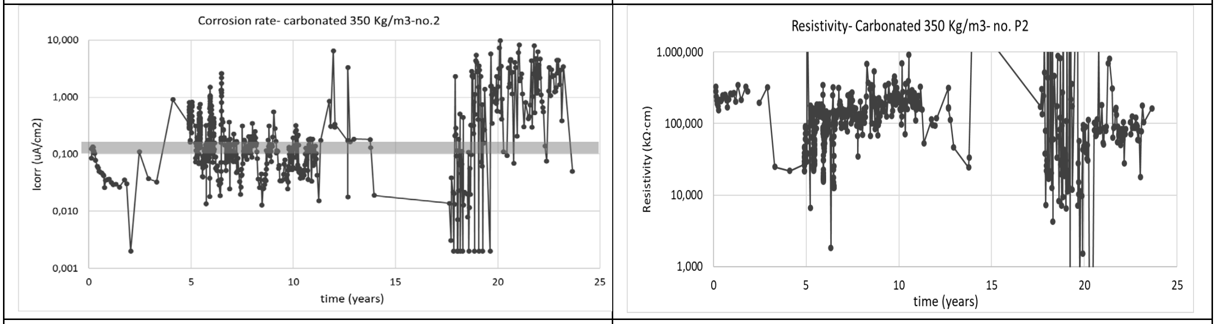
In figure 3 is shown the evolution of the weight of the specimen no.2. Cycling following the wet-dry seasonal and daily periods are recorded. As the weight was started to be measured after the accelerated carbonation, the increase at the beginning was not due to the carbonation, but to the adaptation to reach moisture equilibrium with the particular chamber where the specimen was held until it was almost 5 years old (chamber at 20ºC and 80% RH in this case). After 5 years the specimen was removed from the chamber and placed outdoors and simultaneously tested by some artificial events to simulate "raining" (submerging the specimen under water). These immersion tests are noticed in the graph by a sharp increase in weight, followed by drying at the normal atmosphere. These cycles were made to understand the wetting and drying performance when rainfall is produced.

After being around 7 years old, the specimen was maintained outdoors for the rest of the testing without any perturbation from artificial wet-dry tests. The period between 7 to11 years life will be later illustrated in more detail. In the period of being around 14 to 17 years old the specimens were not measured, to retake the measurements until they were 23 years old.



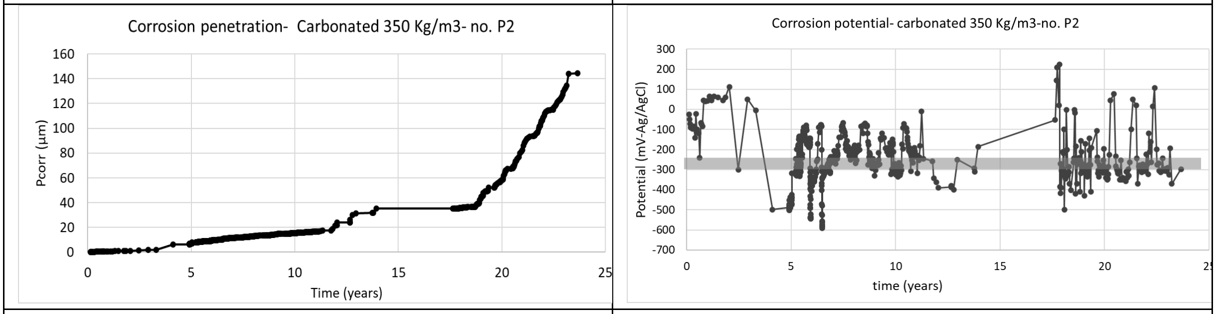
a) Weight evolution

b) Relative humidity (external and internal) and internal temperature



c) Corrosion rate

d) resistivity



e) Corrosion penetration (accumulated corrosion)

f) Corrosion potential

Figure 3 Climate and corrosion parameters in specimen no.2 (350 kg/m3 cement and carbonated)

Although from the beginning it was noticed a decrease in averaged weight with t~~he~~ time, it is more significant during this last period (17 to 23 years) that the weight evolves to be smaller than the original one (just after the accelerated carbonation). That is, it seems that the aging provokes a weight loss (attributed to the evaporation of the combined water likely because the increasing of the polymerization of the C-S-H) due to the evolution of hydration and the long periods of drying in Madrid Summers, with increasing longer periods at high temperatures. It can be summarized that a weight of reference does not exist, because it may decrease with time. This evidence prevents a precise calculation of the saturation degree (referred to the actual porosity that evolves) making more feasible to express the retained water content as “volumetric fraction”, because the specimen volume remains, while the porosity evolves because of the aging effect.

RH/T evolution

It is shown in figure 3b. These parameters were starting to be systematically recorded after 5 years of life with the period 14-17 years without records. As general feature there are cycles that follow the seasonal and the daily RH/T evolution simultaneously to the rain events. The RH inside the concrete is always higher than the external one in this specimen which is not protected from rain. The temperature inside and outside was very similar and that is why only the internal one is shown in the graph. This similarity was attributed to the metallic tube used to insert the RH/T probe that would thermically connect the exterior with the interior of the specimen.

There is a certain increase with time of the annually averaged temperature, but a noticeable increase cannot be concluded. The changes of RH also are similar all around the 23 years of testing (1992-2015).

Corrosion parameters

There are shown in figure 3c (corrosion rate, I_{cor}), 3d (resistivity, ρ), 3e (corrosion penetration, P_{corr}) and 3f (corrosion potential. E_{corr}).

The corrosion rate (Figure 3c) after the initial carbonation was relatively low, because the specimens were in a chamber at 20ºC and 80% RH, with ~~then~~ insufficient humidity to show active corrosion. When after 5 years, the specimen was exposed to the atmosphere and submitted to artificial wet-dry cycles, the corrosion rate increased following the natural and artificial changes of moisture, The maximum values were relatively high, above 5 μA/cm^2 [14]. In the last years of testing the oscillations were very significant following the moist periods, with values until around 10 μA/cm^2.

The evolution of the resistivity (figure 3d) is completely parallel to that of the corrosion rate, but opposite: the corrosion rate decreases when the resistivity increases. There is a slight decrease from the initial values after carbonation to the last testing period, but it can be concluded that the average value is around 110 kΩ·cm with not high scatter.

The corrosion potential (figure 3f) again shows a parallel, but opposite trend to the corrosion rate, with average values around -250-300 mV (Ag/AgCl). The most negative values reached -600 mV and the most positive were around +200 mV. Wide range typical of a carbonated concrete.

Finally, in figure 3e gives values for P_{corr} values which are ~~the~~ integration of the curve I_{corr}-time at each age (14). The trend is very illustrative of the two periods of conservation regimes: a first one inside a chamber with 80% RH and a low corrosion rate and a second stage at the atmosphere with much higher mean annual value of the I_{corr}. In this figure, it is important to notice that not having data between 14 and 17 years the total corrosion penetration (140 µm) is smaller than the real value, because it was assumed that the corrosion rate in that period is small (0.02 µA/cm^2) while the corrosion attack did not stop, but continue increasing.

Closer analysis of the climate effects on the period 7 to 11 years

The period between almost 7 to11 years is taken for a closer analysis on the detailed evolution of the corrosion parameters with respect to the evolution of the climate. First, we will comment on the climate evolution, then that of the weight and finally that of the corrosion parameters.

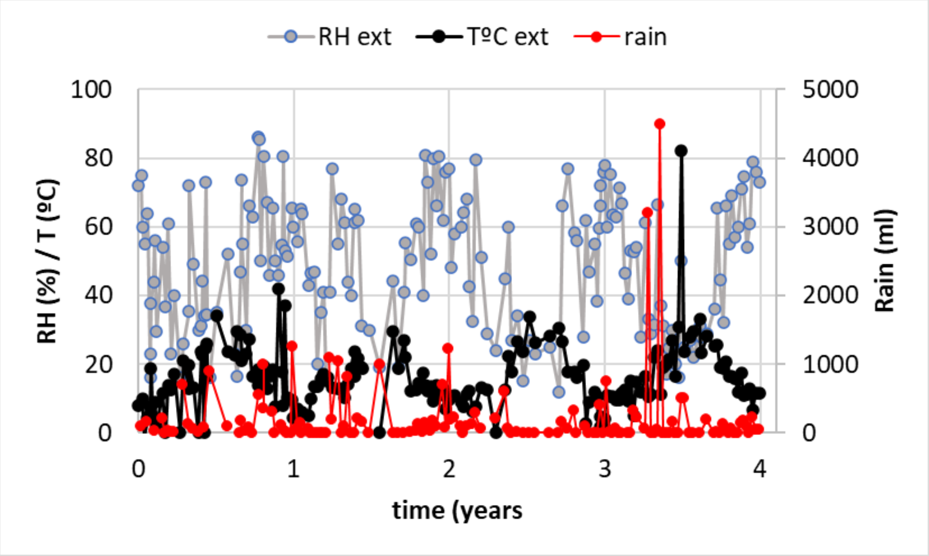


Figure 4 Evolution of weather parameters (RH-EXT, T-EXT and rain events) (the time axis has been started at 0 but the real time life was 4.8 years as in the rest of the figures.)

Figure 4 depicts the evolution of the climatic (named external) parameters (T, RH-EXT and rainfall) showing the seasonal periods with the minimum values of RH-EXT when the temperature is maximum and vice versa. This record shows that the rain events have a transitory impact at short term by a sudden increase in the values of RH in the atmosphere, that later takes certain time to recover the average values. That is, the RH-EXT is temporarily increased during the rain events, introducing a bias in the RH-EXT. This disturbance by the rain appearance prevents to model a continuous evolution of the external climatic parameters, as the rainfalls are unexpected in intensity and duration. Several different alternative scenarios with respect to the duration and intensity of the rain are feasible but this complicates the detailed modelling very much.

To illustrate better the effect of rain, figure 5 shows the relation between RH-EXT and RH-IN in the case of two twin specimens, but one exposed and the other protected from rain. Not only the RH -IN is always higher than the RH-EXT, but that exposed to rain (black points) reaches higher RH-

IN than the protected one (red colours) although with numerous days having similar values. However, given that the amount of retained water is very different in both, as shown in figure 5, it can be deduced that RH is not a good indicator of the amount of water in a concrete exposed outdoors.

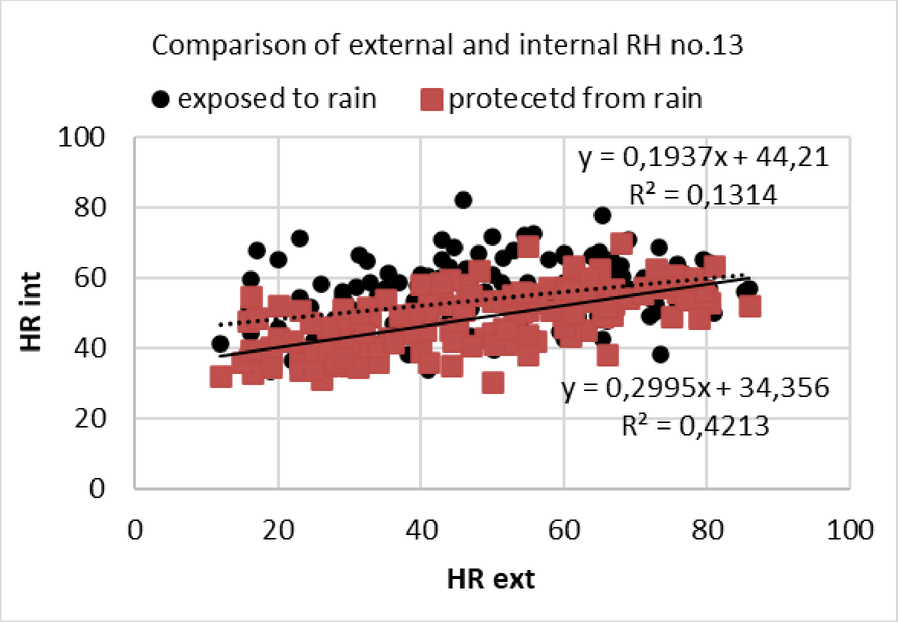


Figure 5 Comparison of RH-EXT and RH-INT of two twin specimens, one exposed to rain and the other sheltered from rain.

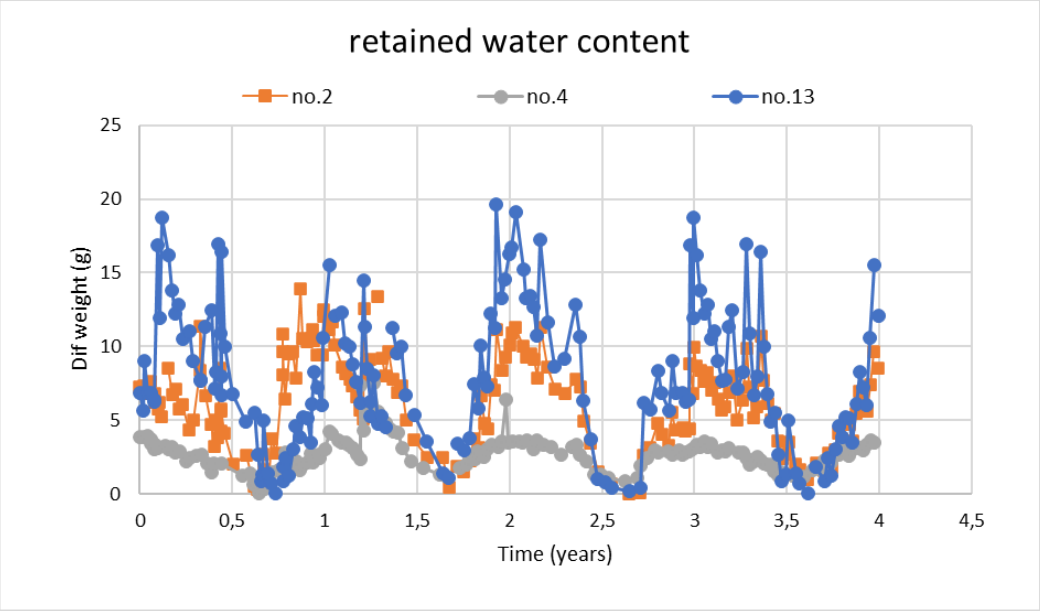


Figure 6 Evolution of retained water content of the specimens.

With respect to the weight evolution, figure 6 depicts the change of volumetric fraction (weight divided by the volume of the specimen) of the specimens listed in Table 1 (three carbonated and one with chlorides in the mixing water) during the same period (6.8 to 10.8 years). The specimens submitted to rain, although present the same trend, they retain different amount of water, fact that can be explained by the different porosities and shape of their pore size distribution. The specimen sheltered from rain (in grey in the figure) retains much less water.

Figure 7 shows the relation between the F_v and the internal RH, indicating the dependence but also showing how the same internal RH-INT is the consequence of very different water contents. The scatter is very high and the regression coefficients relatively low.

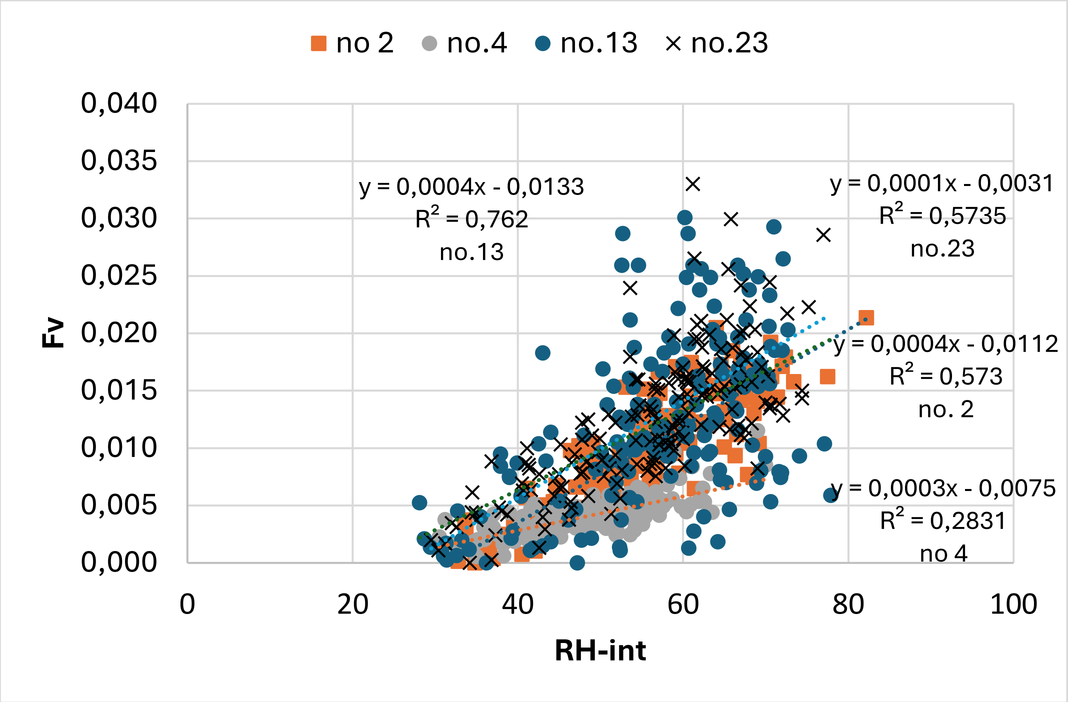


Figure 7. Relation between internal RH and volumetric fraction

Figure 8 shows the evolution of resistivity with time for the three specimens showing that they are different, mainly between been or not exposed to rain. Thus, the lowest values are recorded in the specimen no.13 having the lowest cement content and exposed to the rain. The specimen 4 has been always out of exposition to the rain and shows the highest values because it is drier and has never been wet after curing. The specimen number 2 is twin with the no.4 but shows resistivities similar to the specimen no.13 despite its higher cement content, but with much less difference between wet and dry periods

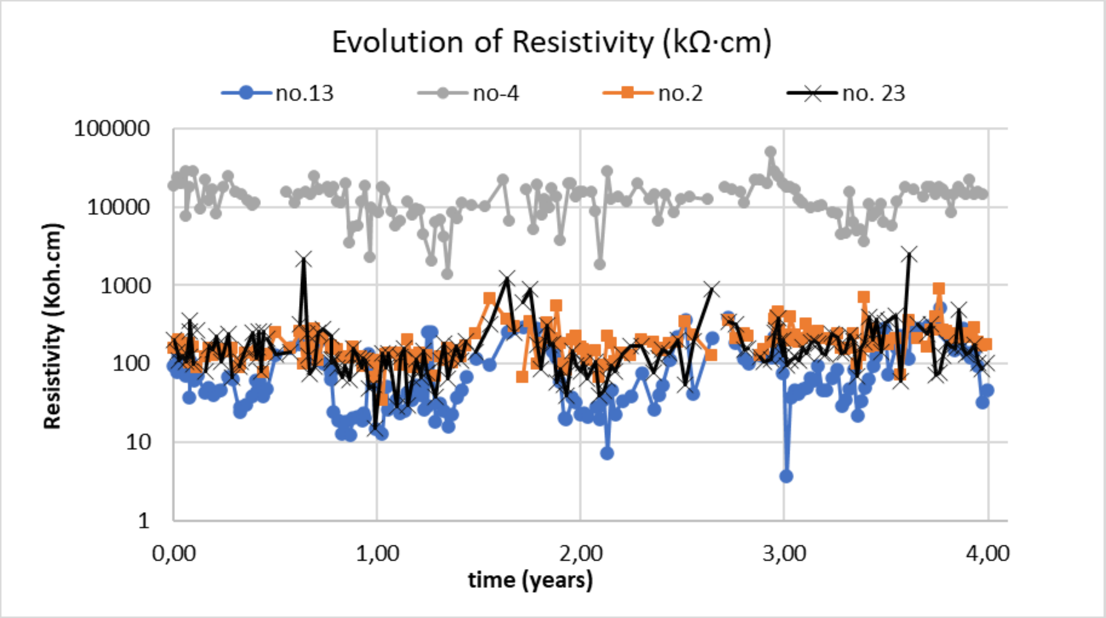


Figure 8 Evolution of Resistivity during the four years period.

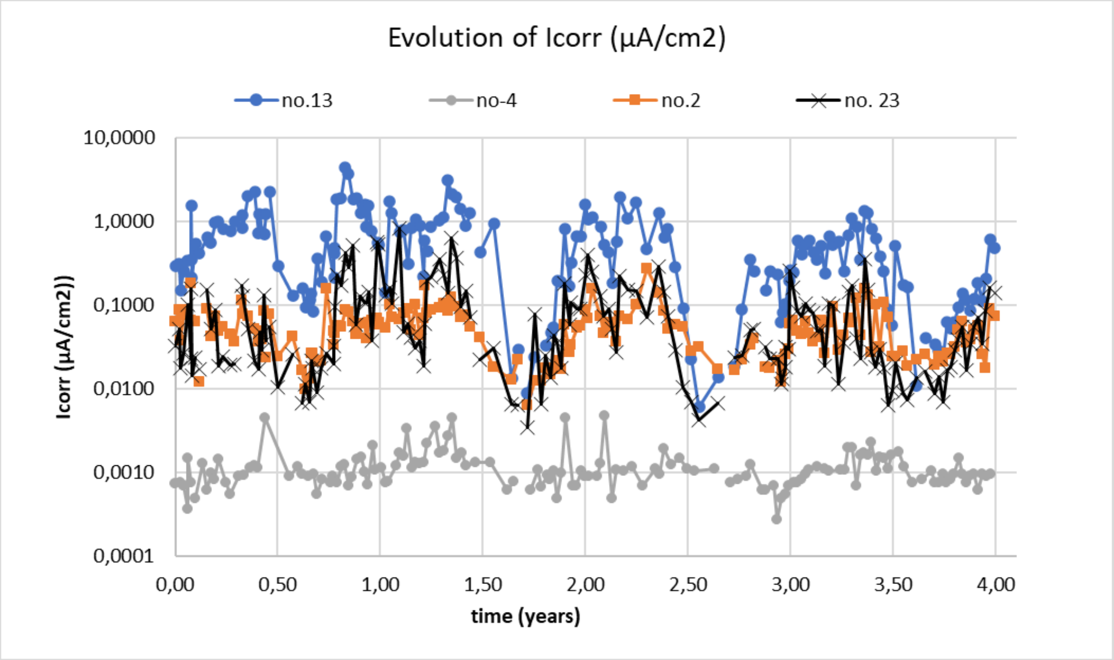


Figure 9 Evolution of corrosion current during the four years period.

The corrosion currents (I_{corr}) in figure 9 shows the low values of the specimen protected from rain (average value of 0.001 µA/cm^2) and the evolution with the seasonal events of those exposed to rain. The specimen showing the highest values is that with the lowest cement content carbonated (no 13 in the figure), while that having 3% of chlorides in the mixing water (no.23 in the figure and trend in black) does not show so high values. This is an important aspect to be emphasized as it is thought that the chloride contamination induces always higher values of corrosion rate than carbonated concrete, while here the results show the opposite (because the resistivity is higher in the chloride contaminated one as shown later). Then, the corrosion rates values would depend on the particular case (particular resistivity) and on the chloride content, being able to be smaller or higher than the carbonated condition.

DISCUSSION

As background, it is important to insist that the RH is the water vapour in the air, and then, water in gaseous phase. A vapour does not provoke corrosion unless it condensates as water drops (liquid water or retained water). This is a usually forgotten aspect that makes many tests applicable to real concrete conditions when they are based on the RH value. The corrosion rate has to be related to the water content (saturation degree or volumetric fraction) and not to the RH, because this one is not univocally related to the water content when the temperature is not constant as is the case of natural exposure.

That is, the RH indicates the amount of water vapour in a cubic meter at a certain temperature, and that is why it is named “relative” and therefore, the total amount of vapour in the air (absolute humidity) may not change when the RH changes, because the RH is relative to the temperature. Also is not related to the water content as for the same RH it might be very different water contents. This is because the system is continuously out of equilibrium due to the continuous evolution of the temperature and therefore the law of Kelvin-Laplace on the maximum pore radius filled with water at a certain RH, or Arrhenius law for changes with temperature, cannot be applied without simultaneous application of the corresponding kinetic laws, because the changes induced are not instantaneous.

An additional principle that is necessary to stress on the water exchange between the concrete and the atmosphere is the reason for the different F_v’s when the rainfall on the specimens is the same. The F_v and the internal RH are a consequence of two different aspects: one is the inside and outside equilibrium of the water vapour (RH-INT) and of the capillarity produced when it is raining. Rain entries by capillarity into concrete and the rate of absorption followed by desorption is another key feature for the resulting F_v. Additionally, the amount of water retained by capillarity after a rain event depends on the temperature and the wind velocity which affects the evaporation rate. In summary, there are two fluids: the water vapour and the liquid water. Their exchanges follow different mechanisms which are dependent as well on the rates (kinetics) and critically, on the temperature.

Trying to understand the complex influence of the weather in the corrosion performance of the reinforcements, neglecting the external RH/T as the controlling parameter of the corrosion rate, analysis should progress on finding the acting controlling variable of the corrosion evolution. Figure 10 shows the relation between the weight difference and the corrosion current allowing to deduce that there is a dependence, but different for each specimen. Thus, the corrosion increases when the retained water is higher, but how high is the corrosion current varies in each specimen, again indicating the importance on the concrete porosity, and of the presence of chlorides with respect to the carbonation. In present specimens, the carbonated specimen with the lower amount of cement is that showing the highest corrosion currents, while, as mentioned, that having chloride in the mixing water presents in this case the lowest corrosion currents of the three exposed to rain.

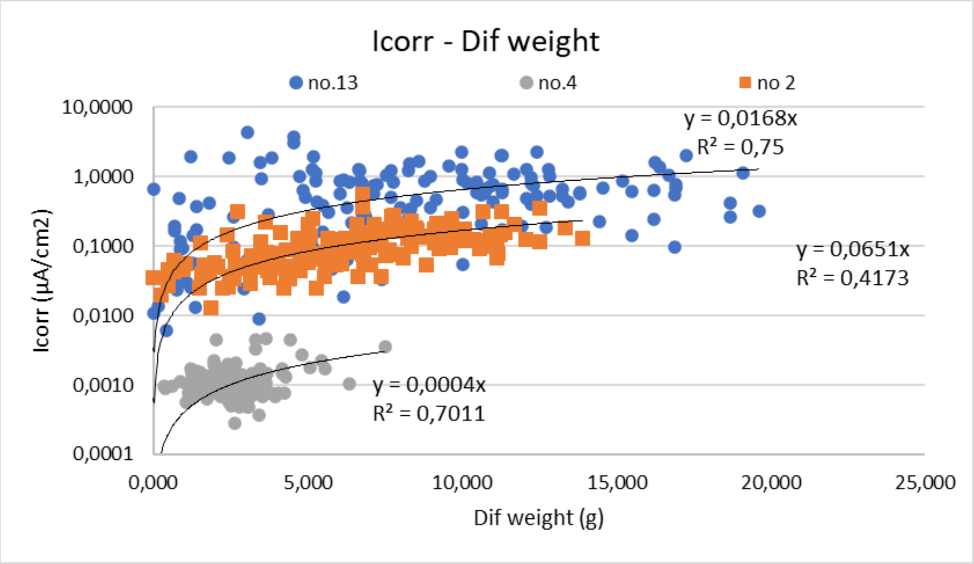


Figure 10 Relation between weight difference (retained water content) and corrosion current.

The relation between the volumetric fraction and the resistivity is given in figure 11, indicating again that there is a dependence but not with a unique relation.

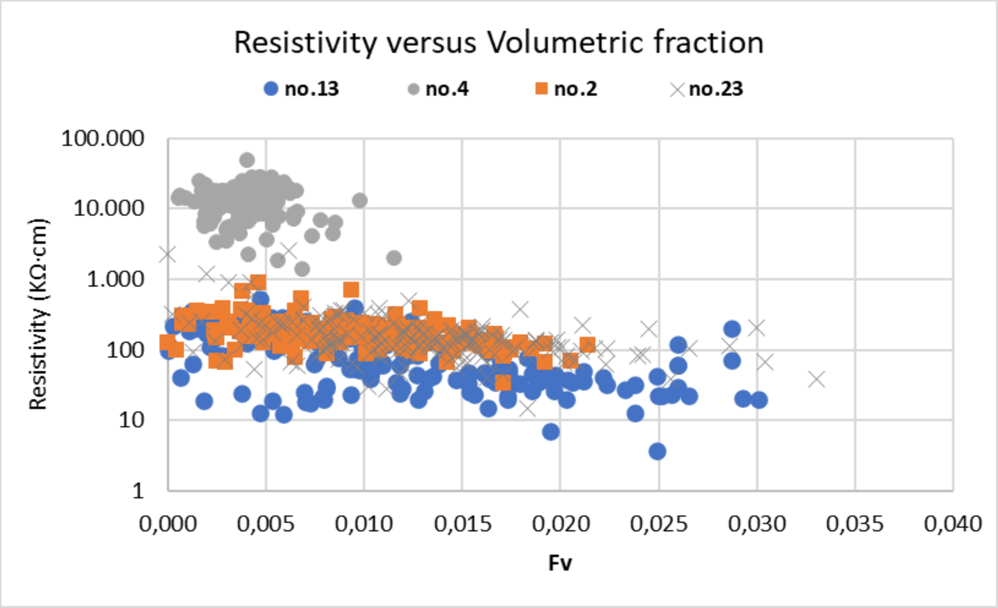


Figure 11 Resistivity of the three carbonated specimens as a function of the volumetric fraction

The same happens when relating the corrosion rate to the $F_{v.}$ (figure 12). There is a dependency, but again not finding a unique relation to $F_{v.}$, enabling to deduce that the microstructure of the concrete is as important as the climate parameters when trying to generalize the relation.

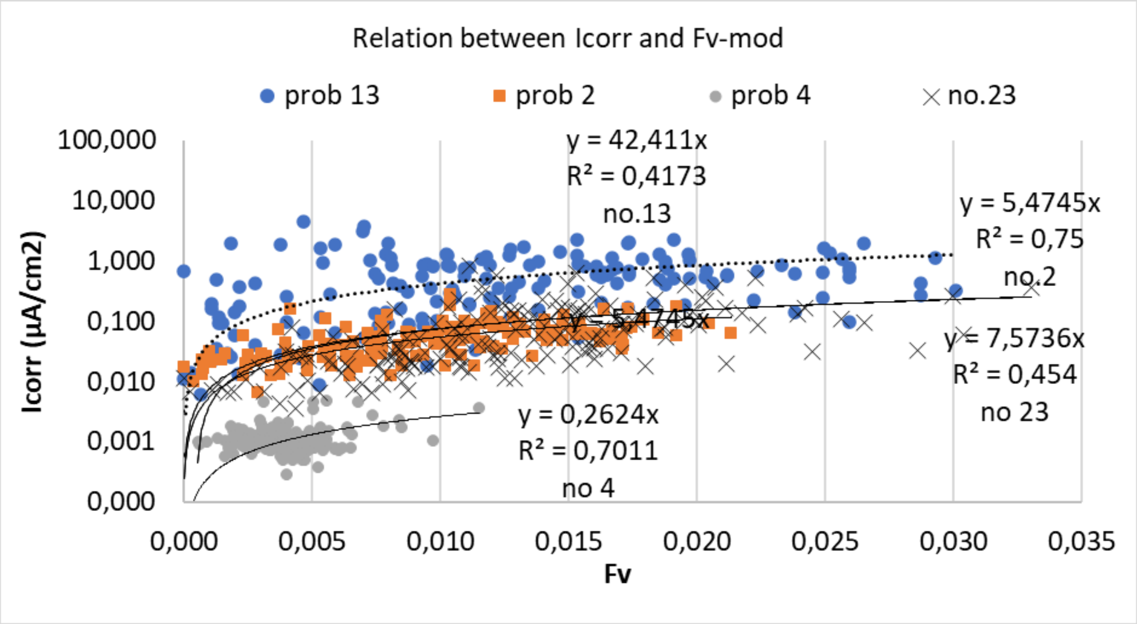


Figure12. Corrosion rate of three carbonated specimens as a function of the volumetric fraction

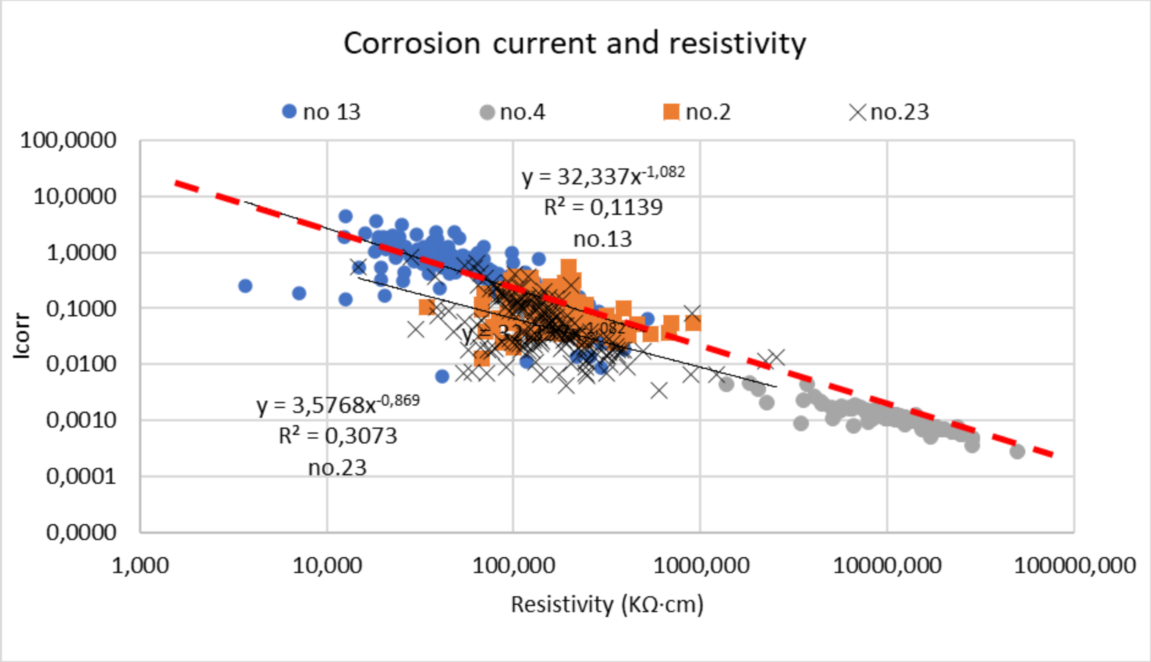


Figure 13 Corrosion rate as a function of resistivity of the four specimens. All the results fit with scatter but showing the trend of equation (3) [16].

Other relationships of the corrosion current with the degree of saturation or the water volumetric fraction give similar trends, indicating the lack of a unique relation between corrosion current and water content. However, when plotting the corrosion current with respect to the resistivity, that unique relation appears as shown in figure 13. Now it is possible to understand why the specimen with chlorides (no. 23) shows lower corrosion rates than the low quality carbonated one (no.13). It is because of the resistivity is higher in the chloride contaminated specimen. When they had similar values because of the degree of saturation, the corrosion rates may be similar.

The graph corrosion current-resistivity shows the trend (in red in the figure) already identified [16] with a slope close to -1 and a value of resistivity of around 260 kΩ·cm for the corrosion current of 0.1 μA/cm^2 (boundary between active and negligeable corrosion). This trend has been confirmed by other researchers [17]. Then, the law behind the plot shown in expression (3) can be accepted as generic and universally applicable to concrete.

$$I_{corr}(\frac{\mu A}{cm^2}) = \frac{26\ (K\Omega \cdot cm)}{\rho} \tag{3}$$

It means that the corrosion rate evolves in parallel (mirror) to the resistivity which is its controlling parameter. However, to generalize the expression regarding the climate impact, as the resistivity of each specimen is different irrespective of the temperature (figure 8), because it depends on the porosity of the specimens, it indicates the need to introduce a concrete microstructural parameter in any expression trying to relate the weather with the degree of water saturation or with the resistivity. Such function should be of the type indicated in expression (4) obtained from the [3] adding some factors, as indicated below.

$$I_{corr}\left(\frac{\mu A}{cm^2}\right) = f_{ext} \cdot f_{un} \cdot f_p \cdot \frac{26\ (K\Omega \cdot cm)}{\rho} \tag{4}$$

- f_{ext} (factor modelling external weather)
- f_{un} (factor of conversion of units to internal conditions)
- f_p (factor modelling porous microstructure)

That is, for linking this unique relation [3] to the weather parameters it is necessary, apart from the external characterization, to link the resistivity to the concrete porosity (pore microstructure). It is necessary to formulate and find the mathematical expressions of the different factors. Without them any prediction will be purely theoretical. Unfortunately, we still lack of them. Any attempt to base the prediction of climatic change impact only in the external temperature or the RH-EXT alone will lead to erroneous conclusions. The still lack of full understanding of all interrelations between all involved climatic parameters and of the kinetics of the processes happening calls for rigorous collection of data on water retaining amounts in real condition, together with resistivity and corrosion current values.

Use of annual averaged values

The daily and seasonal evolution of the parameters introduces the difficulty of the short-term hysteresis on the evolution of all parameters, as soon as the temperature varies or the rainfall is produced. Next it is represented the annual average values that in principle seem are promising possibilities for future prediction.

The relation of the averaged corrosion rate with the average temperature is given in figure 14. The average temperatures are very close. In spite of the few values, the regression coefficients are very poor indicating the lack of any correlation.

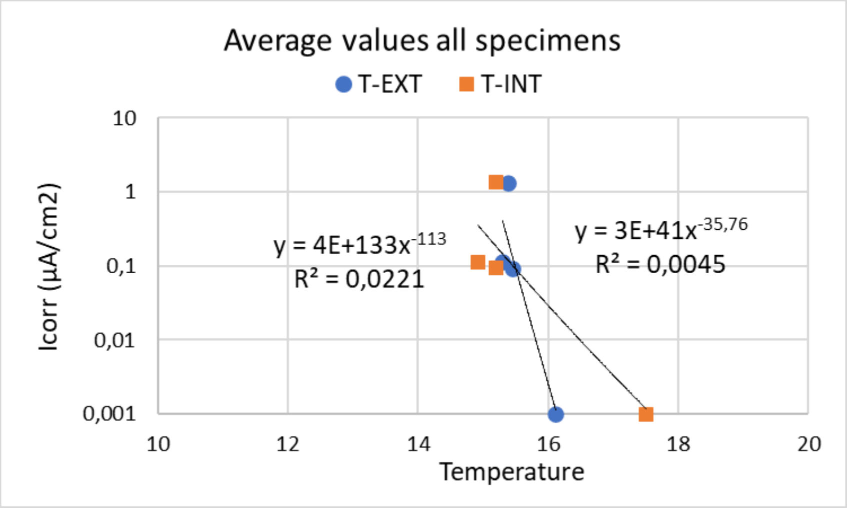


Figure 14 Relation of the averaged value of the corrosion rate of the four specimens with the temperature (T-EXT and T-INT)

Figure 15 shows the relation between external and internal RH with the resistivity and corrosion rate and 16 shows the same but from the saturation degree (S_w). They conclusively indicate that, the external RH-EXT is not the correct parameter, showing a very high regression coefficient however with the RH-INT and the S_w, although they are few points. Why as mentioned, the RH-INT present a high regression coefficient in spite it represents the gas phase and not the liquid phase? Likely because it is an averaged value and not an individual one. The averaging would smooth the transitory evolution and then seem to reflect an equilibrium to the liquid content (degree of saturation)

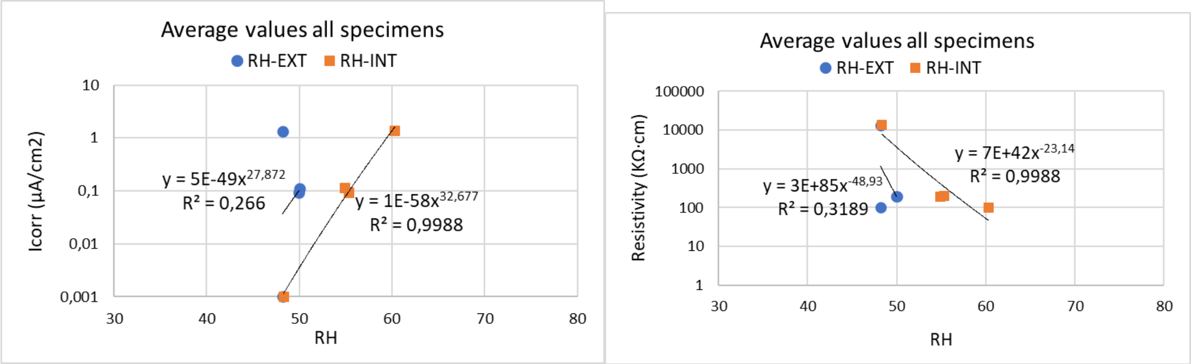


Figure 15 Relation of the averaged value of the corrosion rate and resistivity of the four specimens with the RH-EXT and RH_INT.

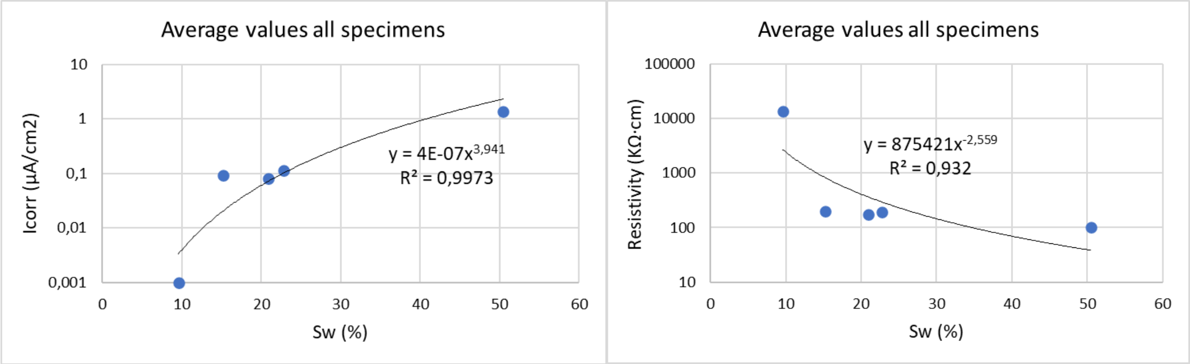


Figure 16 Relation of the averaged value of the corrosion rate and resistivity of the four specimens with the saturation degree (S_w).

A very high regression coefficient is also found if the parameter is the volumetric fraction as given in figure 17, although with the corrosion current is much less precise, because there are aspects, as the chloride content or the previous amount of rust, that might influence the level of corrosion rate. These additional factors need to be studied in the future.

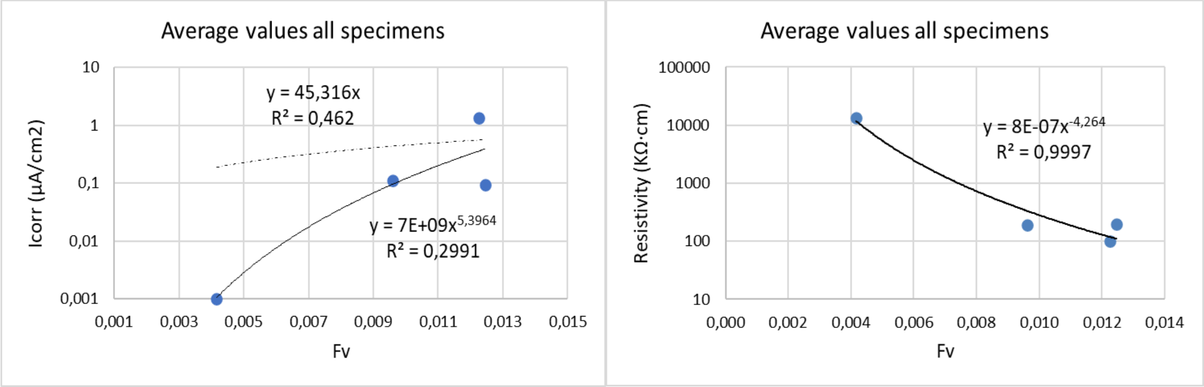


Figure 17 Relation of the averaged value of the corrosion rate and resistivity of the four specimens with the water volumetric fraction (F_v)

These results are very promising, although they are only four specimens (although in different conditions) are presented during only a period of 4 years. They indicate a strong correlation with the water retained inside the concrete. However, it has not been possible until now to find the univocal and significative function relating the external weather, including rain events, with the water retained in the concrete (volumetric fraction) or the resistivity or the corrosion rate. To establish such function will be the next step in the research, extending the study to the whole period and to concrete elements other than these specimens.

Additionally, present results enable to state the incorrect procedure to base the prediction on the external, either temperature or RH, as has been assumed by all the studies claiming to predict the impact of the climatic change published until present [4-11]. It is particularly important a rectification of these conclusions, because until we have not the function relating univocally the external weather with the corrosion rate, it will not be possible to make a prediction with a minimum of precision. This conclusion applies as well to the prediction of the rate of carbonation, because the carbonation in itself is not damaging (even can be positive by fixing carbon dioxide). The only deleterious problem is the reinforcement corrosion.

CONCLUSIONS

The conclusions that can be reached from present results are:

1) The results do not allow yet to derive a general conclusion on the relation between external climatic parameters and the internal concrete conditions, because being exposed to the same weather regime, the specimens have retained different amount of water, attributed to their different pore size distribution (porous microstructure) and in consequence they show different resistivity and corrosion rate.

   The knowledge of the pore size distribution would help to have closer relations between climatic parameters and evolution of concrete water content, although the difficulty would remain as the pore size evolves as well with time because of hydration and carbonation.

2) There is not a unique relation between corrosion current and retained water (volumetric fraction), but it was found with the resistivity, confirming previous works. However, when averaging, not only the resistivity but the RH-INT, degree of water saturation and volumetric fraction, show the feasibility to deduce a strong relation to the corrosion rate.

3) Regarding the full expression to predict the impact in the reinforcement corrosion, in addition to find the external-internal impact, it seems critical the need to introduce a microstructural parameter (named here f_p) into the possible function as indicated by (equation (4)):

$$I_{corr}\left(\frac{\mu A}{cm^2}\right) = f_{ext} \cdot f_{un} \cdot f_p \cdot \frac{26\ (K\Omega \cdot cm)}{\rho}$$

   - f_{ext} (factor modelling external weather)
   - f_{un} (factor of conversion of units to internal conditions)
   - f_p (factor modelling porous microstructure)

The resulting internal concrete conditions will be the interrelation between the concrete porous microstructure and the weather parameters. Any prediction considering climatic change based only in the increasing of temperature or variation of atmospheric RH will lead to erroneous conclusions. We need first to known know which is the impact of climate on the internal concrete moisture conditions. Only after that advance, the impact of climatic change scenarios can be addressed.

ACKNOWLEDGEMENT

For this paper I selected one of the most challenging subjects for me. One where I have more questions. It is a tribute of recognition and admiration to the contributions to the research area and the profession of Hugo Corres and Antonio Marí. Both are examples of perseverance and aspiration to excellence, in addition to their great vocation for teaching. They are also examples

of going beyond our country's borders to compete internationally. I worked on a Spanish project on Rehabilitation, being Tony one of the partners, where he demonstrated his innovative spirit. With Hugo I have worked in several subjects for the last years, especially since his presidency at *fib* where his restless spirit has driven several innovative initiatives. This contact at *fib* has allowed me to establish a very enriching professional relationship, which continues to this day. Thank you, Hugo and Toni, for your contributions.

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