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Monitoring corrosion in concrete by means of Electrical Resistance Probes

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Abstract

Carbonation and chlorides are the main reasons for deterioration of concrete, caused by corrosion of rebars. Controlling the corrosion in concrete by means of a system able to monitor corrosion's parameters, such as potential, pH or corrosion rate, represents a powerful way to prevent concrete deterioration and to reduce restoration's cost of the damaged structure. The aim of this work was to test Electrical Resistance Probes (ERP), usually applied to corrosion measurements in pipelines or tanks, by embedding them in concrete to monitor and estimate rebars corrosion rate. Five ERP probes were embedded into two cylindrical concrete samples, together with four steel rebars. The samples were exposed to chloride penetration and carbonation. Free corrosion potential and corrosion rate values of the rebars were monitored, by means of corrosion resistance polarization measurements (1), in comparison with the loss of metal provided by the ERP system. At first, samples were submitted to accelerated exposition to the aggressive agents, then the exposition was carried forward in "field" conditions and for long time. Comparing rebars corrosion rate with respect to ERP data, the effectiveness of using this kind of probes in concrete was estimated. ERP probes were able to register the start of corrosion with fair precision and good answer quickness.

Keywords: corrosion monitoring, ERP, concrete, carbonation, chlorides.

Introduction

The most common techniques used to monitor the corrosion in concrete require electrochemical measurements on rebars and chemical analysis of concrete that form the bar-cover. To perform these techniques it's necessary to drill the concrete surface, to expose the steel's surface or to take probes from concrete, but these techniques cause more damage to a structure that is already damaged. Using a monitoring system to access to rebars corrosion, such as free corrosion potential or corrosion rate, could be useful to promptly act on the structure, reducing damages and ordinary and extraordinary maintenance costs. The use of embeddable probes to monitor corrosion parameters in concrete has been studied and tested in literature but it seems not to find practical use in real cases in which it's still common practice to intervene on the damage after it occurs and non to prevent it.

The aim of this work was to use embedded probes in concrete to simulate steel rebars and its behavior during corrosion and to measure the loss of metal during the exposure to corrosive environments. This type of probes is already on sale for several years (2, 3, 4) and it's used for corrosion/erosion measurements of metal in fluids, such as in pipelines or tanks. They are known as Electrical Resistance Probes (ERP) and their operation principle is based on Ohm's Second Law. In fact during the corrosion, these probes are able to measure the

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changes in the electrical resistance of a metal in contact with aggressive agents. The resistance change is converted into change of the thickness of the metal, therefore it can be related to the loss of metal due to corrosion.

In literature (5) there are several examples concerning application of devices realized using this principle to monitor corrosion in concrete rebars. Such devices, tested in real structures, showed good behavior, efficiency and congruency even in long time exposure.

The probes tested during this work were not experimental devices realized ad-hoc, but commercial probes with the relative hardware and software able to transform the value of the resistance into the thickness of corroded metal (Fig. 1).

Methodology

In this experimentation, five ERP probes were used. These probes were made of steel with three different thicknesses (Fig. 2), as reported in the datasheets, where a correspondence with their timelife is indicated (Tab. 1).

Four cylindrical concrete probes were manufactured: two were used to embed the five ERP probes; the other two were designed for chloride analysis of the powder and carbonation colorimetric tests, in order to verify the progress of the aggressive agents into concrete. The probes were tested in the typical aggressive environments for steel rebars: carbonated concrete and concrete with chloride presence. The first sample (Cl1), embedding three ERP probes (ERP1Cl, ERP2Cl, ERP3Cl, Tab. 1) and two steel rebars, was designed for chloride penetration. The second sample (CO₂1), embedding the remaining two ERP probes (ERP1CO₂, ERP2CO₂, Tab. 1) and two steel rebars, was designed for carbonation. Inside each of the two cylindrical samples, there was a stainless steel counter-electrode and a seat for the Saturated Calomel Electrode (SCE) placement, in order to take free corrosion potential and corrosion rate measurements (Fig. 3). The cylindrical probes were 16 cm high with a diameter of 16 cm. The bar-cover was 1 cm, both for the rebars and for the ERP probes. In order to accelerate the penetration of the aggressive elements into concrete, the water/cement ratio was 0.8.

Before exposure, the top and the bottom of the two concrete samples were painted with epoxy insulating paint. In this way, the aggressive pollutant was able to penetrate only in the radial direction of the cylinder. The experimentation was led in three subsequential steps.

In the *first step* (concrete curing and corrosion initiation) the four cylindrical probes were manufactured, de-moulded after two days and then cured for 60 days placing them in laboratory (UR =50% ± 10%, T=20 °C ± 1 °C). After this period, CO₂ and chlorides exposure began.

The two probes named CO₂1 and CO₂2 (the last designed for colorimetric tests) were placed inside a hermetic chamber. Carbon dioxide was put into the chamber and its concentration was maintained steady over time by means of an automatic system of flux adjustment. Internal environment conditions of the chamber were as follows: 2% of CO₂ in volume, UR 60% ± 10% and temperature 21°C ± 1°C. The concrete probes were maintained inside the chamber until carbonation depth of the concrete reached 4 cm. This value was largely greater than the cover-bar, in order to promote the steel depassivation.

The two probes named Cl1 and Cl2, (the last designed for powder samplings) after the curing period were submitted to weekly wet-dry cycles in a water solution of NaCl 2.5% by weight, constituted by one day of wetting and six days of drying.

Weekly measurements of rebar free corrosion potential and corrosion rate were taken both for the CO₂ probes and for the Cl probes. For the Cl probes the measurements were taken both before and after each wetting period.

The *second step* (accelerated progress of corrosion) took place after the 9th wet-dry cycle in NaCl solution, when chloride analysis on the cement powder showed a Cl⁻ concentration in the Cl probes greater than 4% with respect to cement weight at the bar-cover. At that time the CO₂ probes showed a carbonation depth of about 4 cm. During this step all the probes were submitted to wet-dry cycles in tap water, maintaining the same procedure of the previous wet-dry cycles in NaCl, in order to promote accelerated progress of the corrosive phenomenon both for rebars and for the ERP probes. Likewise the previous step, rebars free corrosion potential and corrosion rate measurements were taken weekly, before and after each wetting period.

The *third step* (real atmosphere exposure) began after the 16th wet-dry cycle in tap water. The two probes named CO₂1 and Cl1, containing all the five ERP probes, were placed outside in a marine-rural environment for long time spans, taking rebars potential and corrosion rate measurements at the end of each time span.

The five ERP probes were monitored during all the three steps of the experimentation. The value of metal loss given by the probes was acquired separately during periods of time of (1 to 2) h for each probe. At the end of every acquisition, arithmetic mean of the obtained values was calculated to obtain a single value for each acquisition, for each probe. The acquisitions had been taken with a frequency of 1 measurement every (2 to 3) days during the first step, but they were spaced out in the second step and finally, in the third step they had been taken only between a time span of exposure and the following.

Open circuit potential values were measured by means of a high impedance digital multimeter, using a SCE reference electrode, while polarization resistance measurements were carried out using an Amel workstation (566 function generator, 549 potentiostat, 621 differential electrometer) managed by a software suitably developed for using the Acquisition Board NI-AT-MIO-16 (12 bit, 100 ksample/s). Polarization resistance was calculated from the average slopes of potential/current curves obtained from two subsequent galvanodynamic scans (scan rate: 0,5 μA/s): the first one in the cathodic direction and the second one in the anodic direction, each of them starting from the open circuit potential. The polarization potential reached after these two scans was checked to be always equal or less than 5 mV to the corrosion potential. From the polarization resistance value, the corrosion current i_{corr} was calculated using the Stern–Geary equation (1), considering $B = 26$ mV; corrosion rate v_{corr} was calculated as penetration depth versus time (μm/year).

The experimentation ended after 640 days (1.75 years). At the end of it both probes and the rebars were submitted to visual analysis of the metallic surfaces, to confirm corrosion phenomenon and to compare the results obtained from the different measurements that were performed.

Results and discussion

CO₂ exposure. Corrosion rate measurements (v_{corr}) of the two steel rebars embedded in CO₂1 specimen during the whole experimentation are shown in Fig. 4. It can be noticed that, during curing time of the specimen, v_{corr} values were smaller than 10 $\mu\text{m}/\text{y}$ but they didn't increase significantly during CO₂ exposure. Otherwise, during the second step, v_{corr} values considerably grew starting from the first wet-dry cycle, showing variations between 5 $\mu\text{m}/\text{y}$ in the dry period and 30 $\mu\text{m}/\text{y}$ in the wet period. This phenomenon indicates that the corrosion was initiated. In fact, it only can take place if the surface of the steel, after being depassivated, is reached both by oxygen and humidity. Finally, during the third step, low values of v_{corr} were reported, if compared with the previous ones. That happened because concrete was never able to be completely soaked during raining periods, as it was during wetting cycles.

To uniform the data and to compare v_{corr} measurements obtained from the two rebars to the values given by the two ERP probes, the curve reported in Fig. 4 was integrated with respect to time in order to obtain the loss of metal over time, expressed in μm . The data given by ERP probes was already expressed as a loss of metal over time, but at the start of the experimentation each probe provided a constant value that was different from zero. For this reason, all the data given by the probes have been reported on the same chart subtracting the corresponding zero-time value from the measured data, as shown in Fig. 5.

Despite the data obtained from the two ERP probes, ERP1CO₂ and ERP2CO₂, were dispersive, especially during the first step, a growing trend can be noted, defined by segments with different slopes. A significant slope increase is found to be that corresponding to the second step of the experimentation, which was characterized by the highest corrosion rates.

ERP2CO₂ showed corrosion initiation and progress better than ERP1CO₂. At the end of the experimentation ERP2CO₂ reported a total loss of metal comparable to the loss of metal of the rebars, which was about 11 μm . This probe was also the most sensitive one, according to Tab. 1, having a metal thickness of 500 μm , halfway the thickness of the other ERP probe. In fact ERP1CO₂ showed more dispersive values than ERP2CO₂ and its total metal loss was lower compared to the rebar metal loss (about 7 μm), despite its curve showed a growing trend too.

Corrosion of steel due to carbonation is a phenomenon that occurs in a widespread way all over the steel surface in contact with carbonated concrete and this fact is visible also from the pictures of the rebars (Fig. 6) and of the ERP probes (Fig. 7) pulled out from CO₂1 concrete specimen at the end of the experimentation.

Chloride exposure. Corrosion rate measurements (v_{corr}) of the two steel rebars embedded in C11 specimen during all the three steps of experimentation are shown in Fig. 8. The curve shows that, during curing time, v_{corr} was lower than 10 $\mu\text{m}/\text{y}$ and it gradually grew during chloride exposure, reaching values between 20 $\mu\text{m}/\text{y}$ and 60 $\mu\text{m}/\text{y}$ during wet-dry cycles in tap water. Every measurement performed before and after the wetting period of each cycle showed variations of about (30 to 40) $\mu\text{m}/\text{y}$ between dry and wet period. In the third step, as occurred for CO₂ specimens, v_{corr} values were lower compared to the previous ones, despite they were never below 20 $\mu\text{m}/\text{y}$.

As for the previous CO₂ specimens, data were processed in order to compare ERP values to rebar v_{corr} values for Cl specimens too, obtaining the loss of metal as a function of time (Fig. 9). In ERP3Cl curve an abrupt increase of slope took place starting from the second half of the first step of experimentation, after 7 wet-dry cycles in chlorides. The same curve stops after a loss of metal of 200 μm , occurred after about 0.7 y (~ 8.5 months). This value matches the thickness of the metal present in ERP3Cl probe. In fact after 8.5 months a hole was formed in ERP3Cl probe and it stopped working properly (Fig. 10). ERP2Cl probe, characterized by a metal thickness of 500 μm , showed a similar behavior, although spaced in time: its curve had an abrupt increase of slope starting from the second half of the second step of experimentation. Nevertheless, this probe worked properly until the end of experimentation, providing a final loss of metal of about 250 μm . This value was greater than the final metal loss of the rebars due to the localized corrosion attack on the ERP metal (Fig. 10). ERP1Cl curve (metal thickness = 1 mm) showed a final loss of metal that was between the two rebars and at the end of the experimentation it didn't show localized corrosion attack (Fig. 10). Finally, for all the three ERPCl probes, the final loss of metal was one order of magnitude greater than that obtained from ERPCO₂ probes.

Analyzing the expansion (Fig. 11) of the curves showed in Fig. 9 during the first step, it can be pointed out that a change of slope happened for all the elements held in Cl1 concrete specimen, because of the growth in the corrosion rate occurred during wet-dry cycles in chlorides. These curves also show how the three ERPCl probes provided data characterized by a lower scatter if compared to the ones in CO₂1 specimen.

Conclusions

Five ERP commercial probes have been tested embedding them in two concrete specimens exposed to carbonation and chloride penetration. The experimentation was carried on for 1.75 y, divided into three steps: concrete curing and corrosion initiation, accelerated progress of corrosion, real atmosphere exposure. Along with the ERP probes, four steel rebars were monitored by means of open circuit potential and corrosion rate measurements.

The behavior of ERPCO₂ probes and ERPCl probes was very different because of the corrosive attack that took place on the metal surface: generalized attack for the first ones and localized attack for the second ones. This influenced the final metal loss of every element held in the two concrete specimens, with a difference of one order of magnitude between the final loss of metal of CO₂1 elements and the one of Cl1 elements. This fact was confirmed by visual analysis on the metal surfaces of the elements pulled out from the concrete specimens at the end of the experimentation.

The change of slope characterizing every step of the experimentation showed that ERP probes can be used in concrete to detect corrosion initiation, especially for chloride corrosion. The thickness of the metal which ERP probes are made of is very important too, because it directly affected the data scattering and, as a consequence, the ERP probe sensibility: the ERP probe that provided best results was ERP3Cl, characterized by the lowest thickness and lifetime.

It's not to forget that this experimentation was carried on in accelerated conditions in order to observe corrosion results soon, while in a real structure exposed to natural aggressive agents corrosion kinetics could be very low or absent for long initial periods and after corrosion initiation the slopes of the curves could possibly be lower than the ones obtained

from this experimentation. All things considered, for practical real application of ERP probes in concrete structure, a probe characterized by low thickness and high sensitivity is recommended.

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Tables

Tab. 1 - Technical data of ERP probes.

ERP name	Thickness (μm)	Timelife (months) (corrosion rate supposed: 0.5 mm/y)
ERP1Cl, ERP1CO ₂	1000	12
ERP2Cl, ERP2CO ₂	500	6
ERP3Cl	200	2.4

Figures

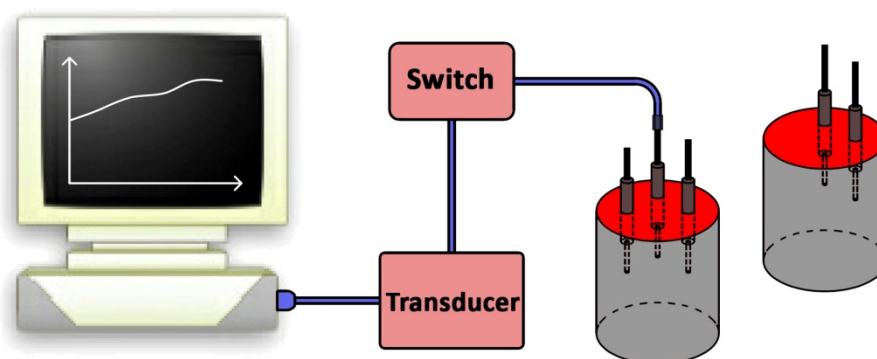


Fig. 1 - Diagram of data measurement and acquisition system for ERP probes



Fig. 2 - ERP probe before embedding it in concrete specimen.

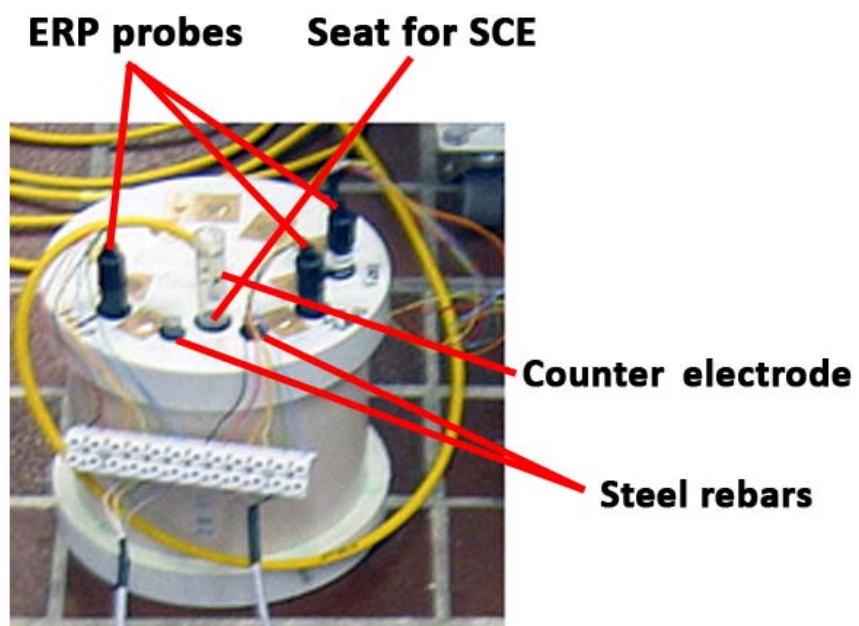


Fig. 3 - Picture of the form used to cast concrete specimens.

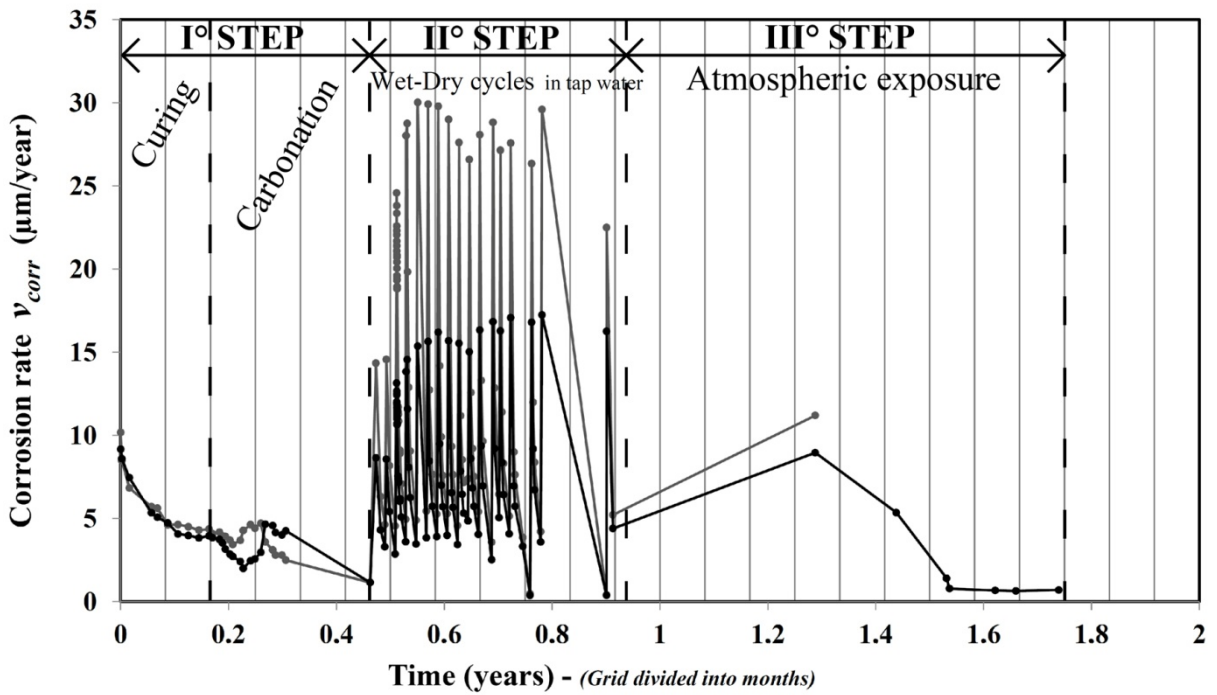


Fig. 4 - Corrosion rate of the two rebars contained in CO₂1 specimen (Stern&Geary method (1)).

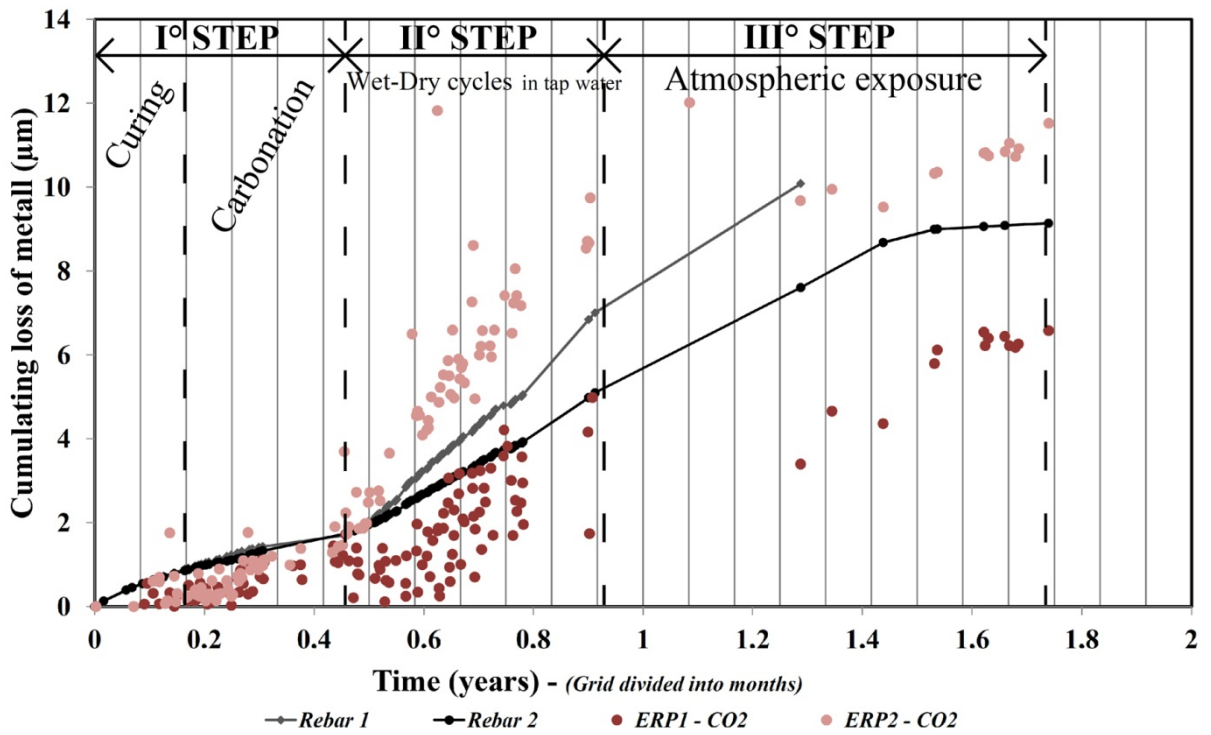


Fig. 5 - Cumulating loss of metal of rebars and ERP probes contained in CO₂1 specimen.



Fig. 6 - Rebars pulled out from specimen CO₂1 at the end of the experimentation.



Fig. 7 - ERP1CO₂ probe (up) and ERP2CO₂ probe (down) pulled out from CO₂1 specimen at the end of the experimentation.

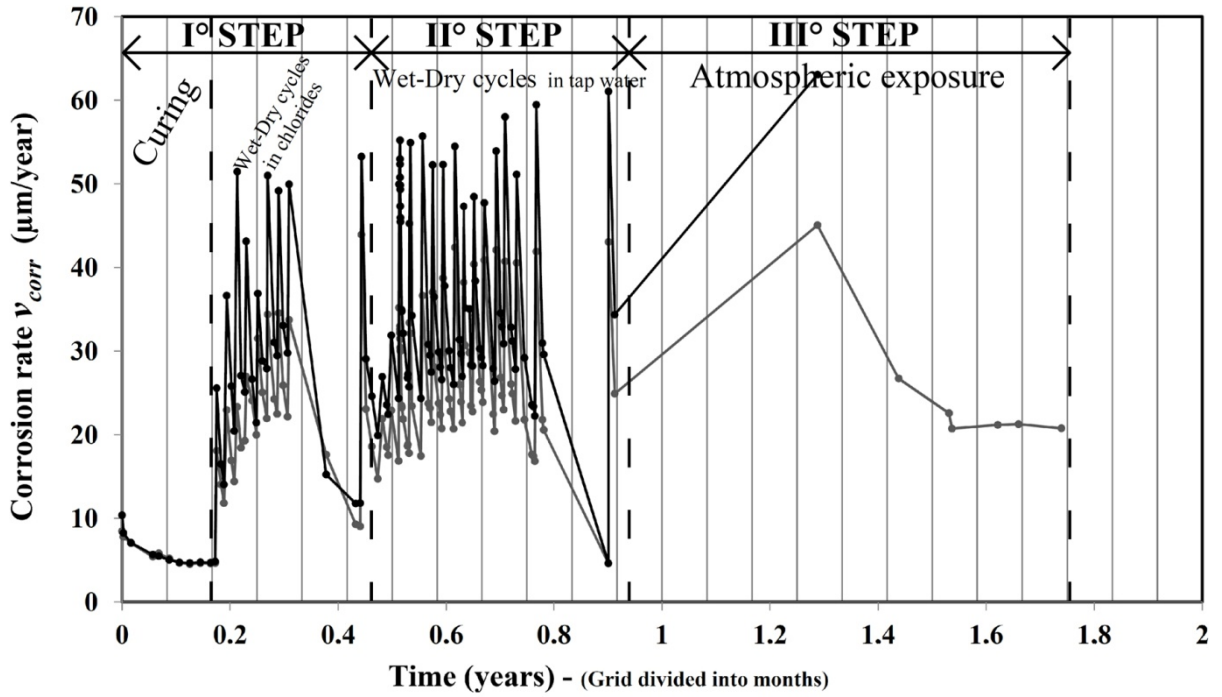


Fig. 8 - Corrosion rate of the two rebars contained in C11 specimen (Stern&Geary method (1))

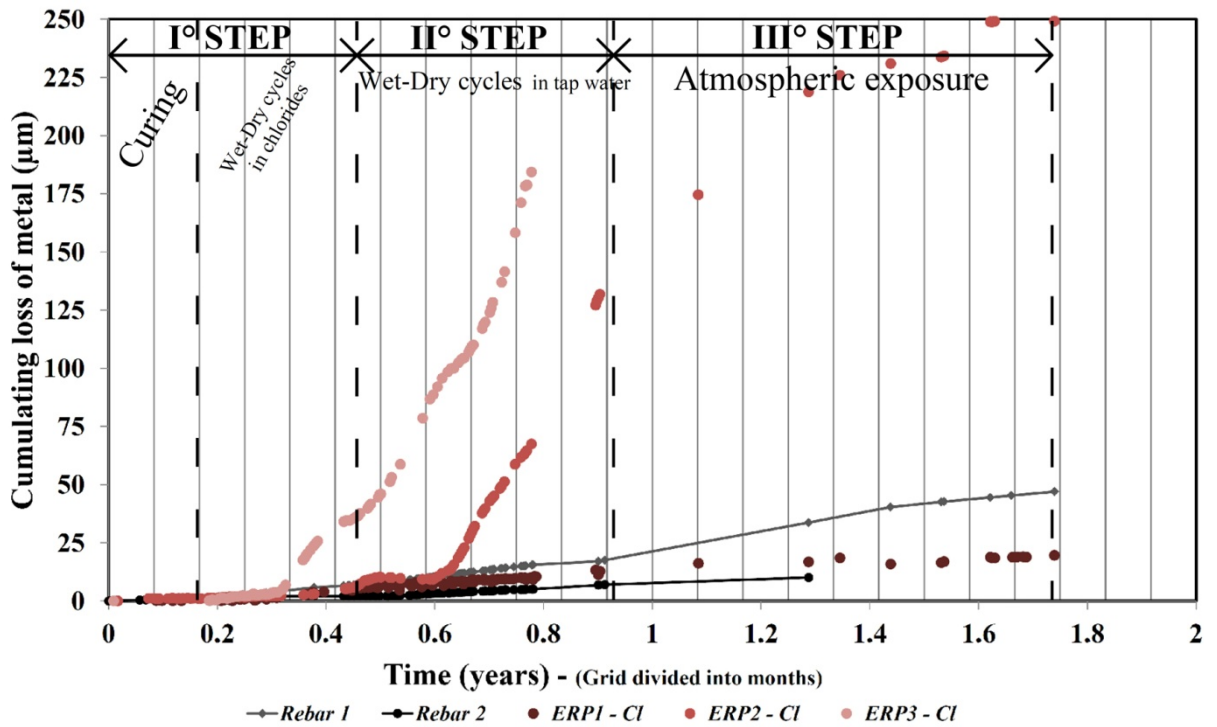


Fig. 9 - Cumulating loss of metal of rebars and ERP probes contained in C11 specimen.



Fig. 10 - Corroded elements pulled out from CII specimen: rebars (a,b) and ERP probes (c).

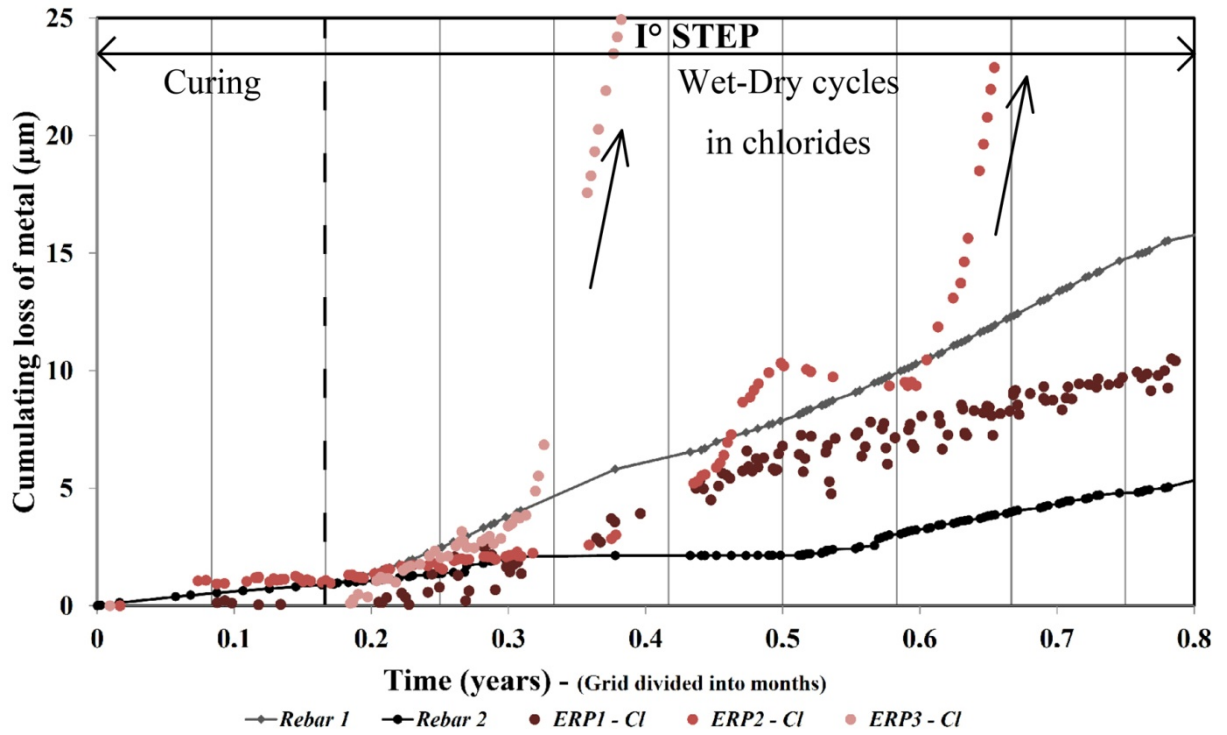


Fig. 11. Enlargement of Fig. 9, first step of experimentation for C11 specimen.