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# Several questions about electrochemical rehabilitation methods for reinforced concrete structures

J.M. Miranda [a,*], J.A. González [b], A. Cobo [c], E. Otero [b]

[a] *Instituto de Metalurgia, Universidad Autónoma de San Luis Potosí, Av. Sierra Leona 550, 78210 San Luis Potosí, Mexico*
[b] *Centro Nacional de Investigaciones Metalúrgicas, CENIM (CSIC), Avda. Gregorio del Amo 8, 28040 Madrid, Spain*
[c] *Escuela Universitaria de Arquitectura Técnica de Madrid, Avda. Juan de Herrera 7, 28040 Madrid, Spain*

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## Abstract

Electrochemical realkalisation (ERA) and electrochemical chloride removal (ECR) have shown their capacity to eliminate, in just a few weeks, the causes of corrosion in reinforced concrete structures (RCS), and for this reason are currently receiving very special attention. Nevertheless, the present state of the art has not progressed enough to dissipate doubts about the efficiency of ERA and ECR as electrochemical rehabilitation methods (ERM) for corroding RCS. A series of highly important questions persist, and continue to be cause of controversy among specialists in the construction sector, which can be summed up in one all-encompassing question, namely:

- *Is removing the sources of corrosion in RCS sufficient to stop rusting?*

To obtain a response to this capital question, electrochemical corrosion analysis techniques are used to study the responses of clean and precorroded steel electrodes embedded in small mortar specimens without chloride additions and large mortar slabs with and without chloride contamination. According to the results obtained, ERM are efficient in delaying the start of corrosion if

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[*] Corresponding author. Tel./fax: +52 44 48 825 4583/4585.
*E-mail address:* jmiranda@uaslp.mx (J.M. Miranda).

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used preventively. However, if applied too late they do not assure the repassivation of rebars with high precorrosion levels and consequently are not useful.

*Keywords:* A. Steel; A. Reinforced concrete; C. Electrochemical chloride removal; C. Electrochemical rehabilitation methods; C. Repassivation

## 1. Introduction

The technical, economic and social importance of the construction industry makes the deterioration of reinforced concrete structures the greatest challenge facing civil engineering in the developed world. Rebar corrosion is acknowledged to be the most influential cause of premature failure of RCS [1].

Let us recall some of the essential and evident aspects of RCS durability:

- The enormous economic costs due to corrosion in general, a considerable part of which—specifically 18%—can be attributed to the construction industry [2]; one of the sectors with the greatest influence on employment and quality of life.
- With regard to building materials, concrete—both bulk and reinforced—is more important than all the others put together.
- The natural state of steel in concrete is the passive state, and if this is maintained then corrosion is insignificant and RCS durability may be considered “almost unlimited”. In fact, it is safe to say that *RCS are being constructed today which will last for centuries with minimal maintenance requirements*.
- However, the carbonation of concrete by atmospheric $CO_2$ and the penetration of chloride ions from the environment to rebar level can destroy their passivity, triggering corrosion and drastically reducing RCS durability [3–5]. This explains why it can also be said that *RCS are being constructed today which will need to be repaired or demolished in 10–20 years*.

ERM, in the form of cathodic protection (CP), ERA and ECR [6–20], thus emerge as very promising means to prevent this rapid deterioration in highly corrosive environments. Interest is focused preferentially on ERA and ECR, since they are much less costly and more friendly to the environment and to worker health than traditional repair methods; while their provisional, short-term nature compares favourably with the permanent character and the continuous maintenance needs of CP.

The practical implementation of all three procedures is highly similar. Use is made of an external current source with an auxiliary anode of the same surface area as the structure: inert and forming part of it in the case of CP; external and frequently of low cost and disposable in the cases of ERA and ECR. All the rebar network is connected to the negative terminal of the current source, forcing it to act as a cathode (Fig. 1).

The present situation is far from satisfactory. This is due in part to the fact that, despite the enormous amount of time and money dedicated to studying RCS corrosion and

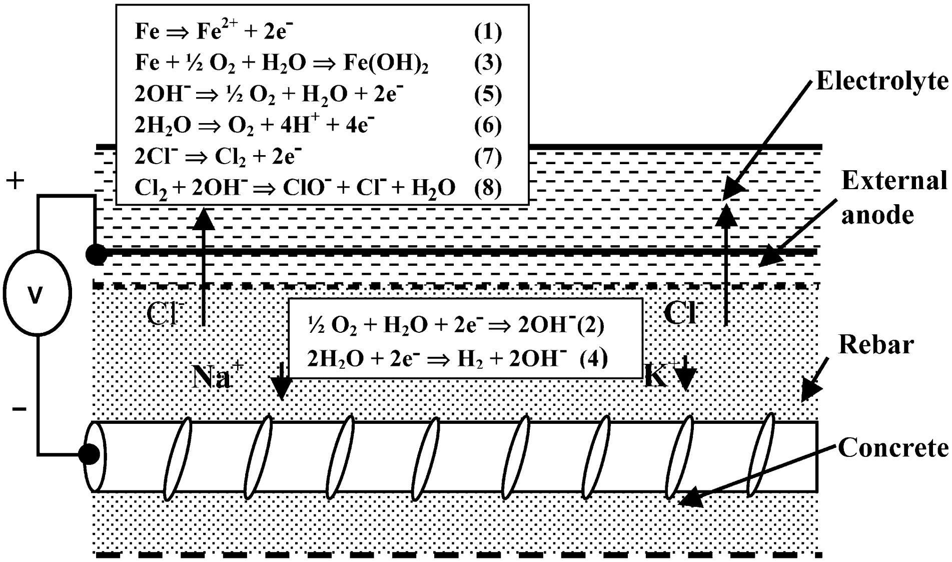

Fig. 1. Schematic representation of ECR and the reactions that take place during the process.

the search for appropriate solutions, controversy continues to surround questions that are of great importance when it comes to taking decisions about corrosion prevention or RCS rehabilitation methods. Paradoxically, these questions are often elementary and would disappear if correct use were made of the knowledge already acquired. This work seeks to propose appropriate answers to some of these questions; specifically the following:

- Is it possible to stop corrosion once it has started?
- Can corroded RCS be repassivated?
- Are ERM for RCS effective; when?
- Is there a relationship between the precorrosion degree of rebars and the possibility of their repassivation?
- Is it sufficient to remove the causes of corrosion in order to halt the attack of corroded structures?
- Can ERM be considered an end in themselves?
- Can a simple potential measurement determine the active or passive state of rebars?
- Do corrosion rates measured before and after the application of ERM have the same meaning?
- Do chlorides continue to be necessary for corrosion to continue once it has started?

For this purpose an analysis is made of the responses of steel electrodes, in clean state and previously corroded, in small mortar specimens without chloride additions and large mortar slabs with and without chloride contamination, using gravimetric, metallographic and electrochemical techniques.

## 2. Experimental materials and methods

### 2.1. Materials

A study has been made of the behaviour of steel plates, in clean state and with different precorrosion degrees, embedded in small cement mortar specimens of 7 × 8 × 9 cm, as shown in Fig. 2, manufactured with a cement/sand/water ratio of 1/3/05. The specimens were always used without chloride ion additions with the aim of guaranteeing the passivation of the clean steel electrodes and causing, if possible, the repassivation of the corroded electrodes. It was attempted to start from the ideal situation, reached after perfect ERA or ECR, in which complete realkalisation or the removal of all the chlorides is achieved; a situation that is impossible in practice.

The following electrode types were used to assess the effect of the steel precorrosion degree on the possibility of its repassivation:

- Clean steel, recently pickled in a 50% hydrochloric acid solution, inhibited with 4 g/l hexamethylenetetramine, thoroughly rinsed in running water and distilled water and then dried immediately with compressed air.
- Steel plates contaminated with 500 mg of $Cl^-/m^2$ and exposed for different times in a humidity cabinet before trying to repassivate them in the mortar. Five specimens were exposed in identical conditions, subsequently removing the oxyhydroxides formed in order to determine the precorrosion degree on three of them, exposing the other two to the action of the mortar.

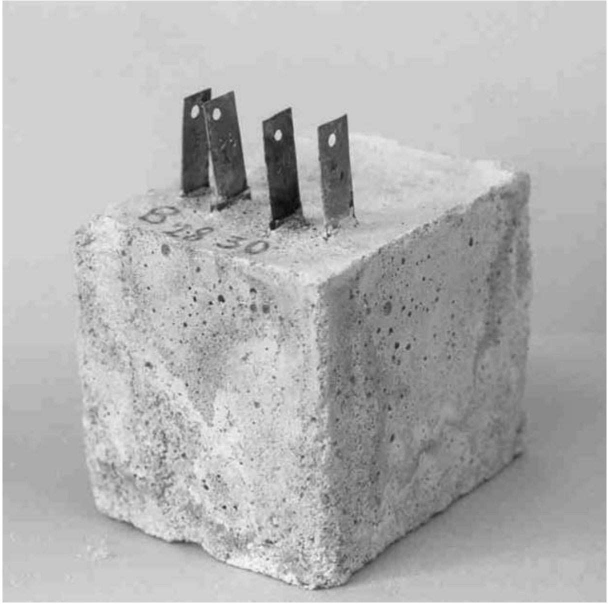

Fig. 2. Mortar specimen with clean and precorroded steel plates embedded in it.

### 2.2. Electrochemical chloride removal

For the performance of ECR, two cement mortar slabs of 133 × 133 × 7 cm were used, as illustrated in Fig. 3, manufactured more than a decade ago with a cement/sand/water ratio of 1/3/0.5 and already considered in previous studies [21–26]. One slab was manufactured without additives, to represent passive structures, and the other with the addition of 3% $CaCl_2$, in order to simulate the behaviour of active structures. Thirteen rebars of 0.8 cm diameter were embedded in each slab at 9 cm intervals, protruding from both sides. The area where the rebars emerged into the atmosphere was insulated with tape in order to prevent differential aeration phenomena.

The tests started with the slabs in very dry state, after several years in an indoor atmosphere of very low relative humidity, normally less than 50%. At the beginning of the study all the surface of the slabs was covered with wet sponges protected by impermeable plastic covers, which were only removed during the performance of $E_{\mathrm{corr}}$ and $R_{\mathrm{p}}$ measurements. For the performance of the potential measurements a saturated calomel reference electrode (RE) was placed on the surface of the slab, being situated in a hole in the centre of a stainless steel cylinder of 7 cm diameter in order to assure its stability (Fig. 3a). One of the rebars acted as the working electrode (WE) and the two adjacent rebars as

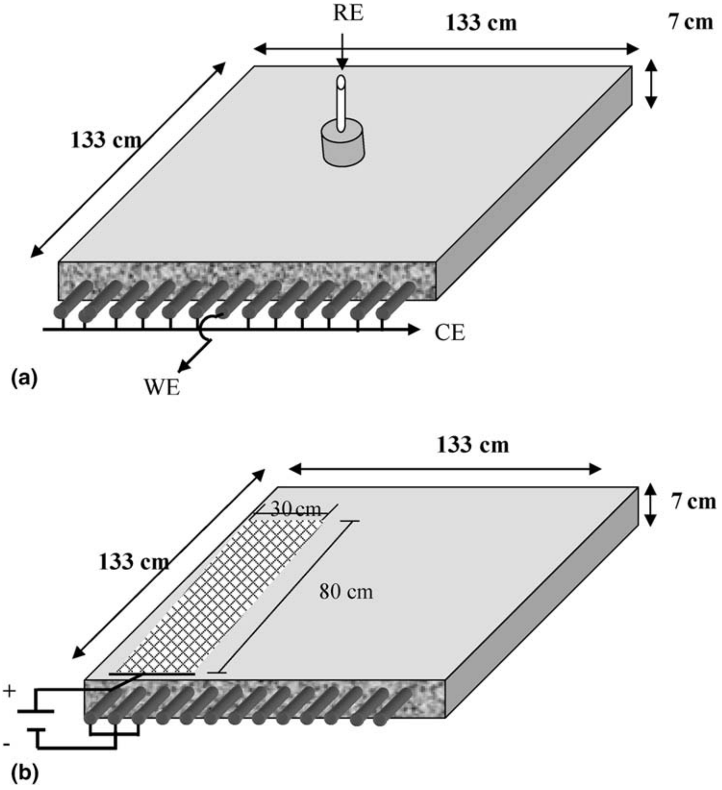

Fig. 3. Schematic representation of the mortar slabs used, showing (a) the situation of the electrodes during $R_{\mathrm{p}}$ measurements and (b) the area where chloride removal was performed.

Fig. 4. Parts of a rebar taken from the slab contaminated with chlorides, showing a high degree of corrosion.

the counter electrode (CE), thus achieving a uniform distribution of the electrical signals across all the WE surface. In the area where chlorides had been removed, a CE of 40 cm in length was placed on the surface of the slab for the performance of $R_p$ measurements.

After several weeks, once a steady behaviour was reached, ECR began, firstly on one side of the slab and then on the other side. ECR was carried out for 6 weeks at a current density of 5 $A/m^2$ in relation to the rebar surface, a rather high value, but which represents 1.2 $A/m^2$ in relation to the mortar surface; within the values usual in practical situations [8]. Nevertheless, it would have been preferable to use a lower current density and to prolong the extraction time in order to reduce the detrimental effects on the mortar. After each removal the evolution of the electrochemical parameters was determined for a time of approximately 2 months. ECR was performed on a slab area of approximately 30 × 80 cm, short-circuiting three rebars to act as the cathode, and using a titanium mesh as the external anode, placing between this and the slab surface a cloth soaked in the $Ca(OH)_2$ saturated solution in order to facilitate the passage of the current. The cloth was wetted twice a week and was covered with an impermeable transparent plastic cover in order to impede the evaporation of the electrolyte. Fig. 3b depicts the set-up used and Fig. 4 shows the high initial degree of corrosion of the rebars in the slab with chloride additions.

### *2.3. Methods*

Both in the small mortar specimens and large mortar slabs, the evolution with time of the behaviour of corroded and clean (passive) electrodes was monitored by means of polarisation resistance ($R_p$) measurements and the plotting of polarisation curves; procedures that allow a quantitative assessment of the corrosion rate, i.e. of the efficiency of

ERM. Periodic controls of the corrosion potential ($E_{corr}$) were also carried out in order to try to deduce, in a qualitative way in this case, whether the corroded electrodes were repassivated or not. It should be noted that, unlike in normal practice, the degree of wetness of the concrete associated with each potential measurement was precisely known.

Prior to chloride removal, the behaviour of the rebars embedded in the chloride-containing and chloride-free slabs was also characterised by determining their $E_{corr}$, corrosion current densities ($i_{corr}$) through $R_p$ measurements, and polarisation curves. This data was subsequently used for comparative purposes to estimate the protective efficiency of the rehabilitation method when chloride ions were removed.

Prior to the removal process, at the end of the process on the first side of the slab, and at the end of the process on the second side, mortar samples (3.2 cm diameter cylinder) were withdrawn in order to determine chloride profiles as a function of depth. The analysis of chlorides was performed on aqueous extracts from the mortar, evaluating with a $(NO_3)_2$-$Hg \cdot H_2O$ dissolution and using a mixed bromophenol and diphenylcarbazide indicator.

## 3. Experimental results

Fig. 5 displays the relationship between $i_{corr}$ values obtained for a uniform current distribution and mortar resistivity for the two types of slab. In a very wide range of resistivities an inversely proportionate relationship is found, in logarithmic coordinates, between the two parameters for active rebars. The resistivity also influences the $i_{corr}$ of the passive rebars, though to a much lesser degree. The consequence is that for very low degrees of pore network saturation, i.e. for very high concrete resistivities, the apparent corrosion rates of the active and passive states tend to approach each other.

Fig. 6 offers a different aspect of the same results, relating resistivity and $E_{corr}$ for the active and passive states. It is shown that the $E_{corr}$ values measured on the slab surface

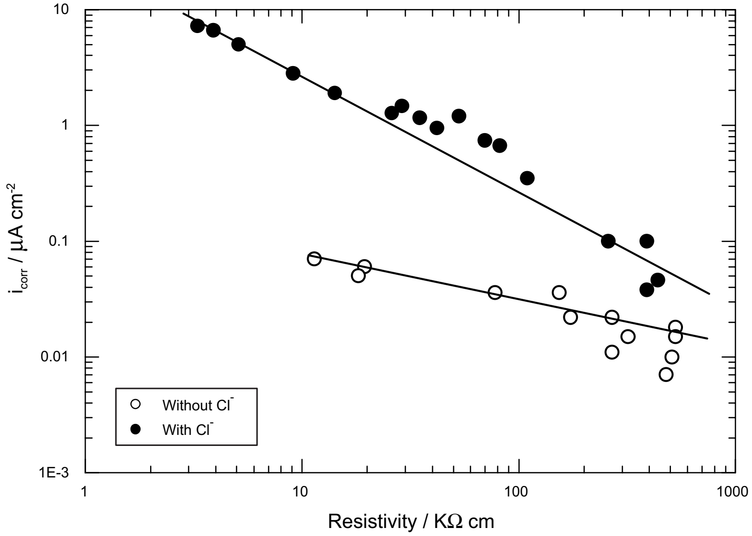

Fig. 5. Relationship between mortar resistivity and corrosion rate of rebars embedded in slabs with and without chloride additions.

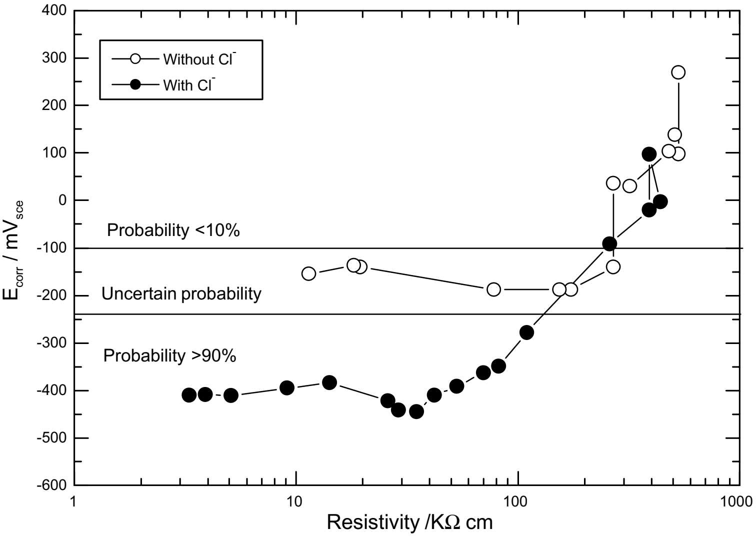

Fig. 6. Variation in corrosion potential of rebars as a function of the resistivity of slabs with and without chloride additions.

drop by about 500 mV with the progressive wetting of the mortar, tending to stabilise for resistivities of <30 kΩ cm, well before the saturation of the pore network is reached. According to the figure, for low degrees of wetness the active and passive structures can be confused if the decision on their state is based only on the $E_{\text{corr}}$.

Fig. 7 shows chloride concentration profiles in the slab before ECR and after its performance on one side and both sides. It can be seen that the initial chloride content is not

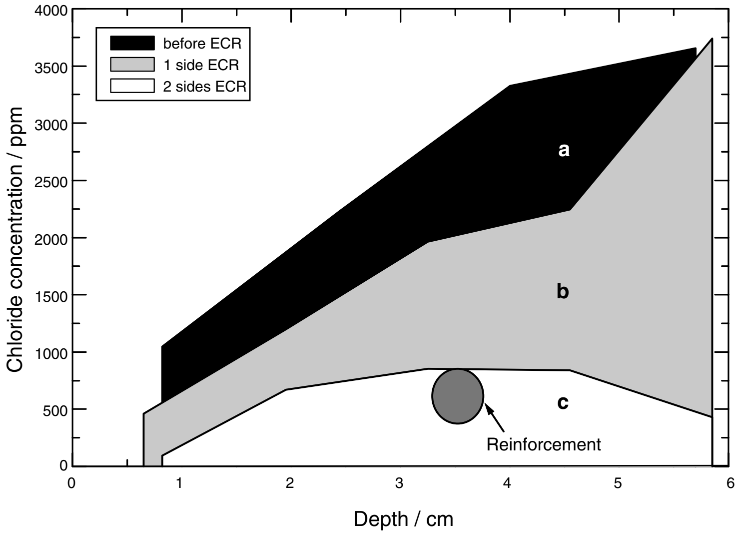

Fig. 7. Chloride concentration profiles of the slab: (a) before removal; (b) after removal on one side; and (c) after removal on both sides.

homogeneous throughout the slab thickness, as the concentration increases considerably with the depth from the upper side of the slab. The repeated wetting of the slab surface for the performance of many measurements over the years has probably shifted part of the soluble chlorides towards the lower surface. After 6 weeks of application of ECR on the first side a clear reduction in the chloride concentration is seen, although the same level continues to be recorded on the opposite side. The reason for this is that since the chloride ions are transported along the current flow lines, comparatively few are extracted

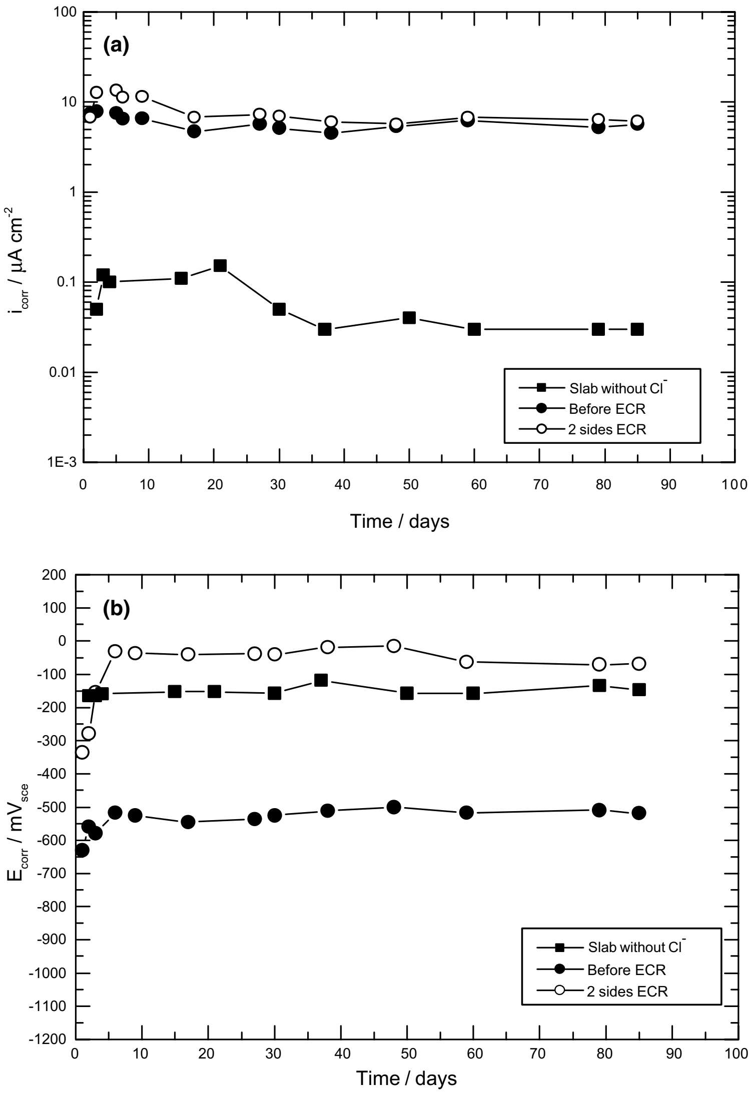

Fig. 8. Comparison of $i_{corr}$ (a) and $E_{corr}$ (b) values for two slab areas, one where ECR has not been performed and the other where ECR has been performed on both sides. For comparative purposes, results are included for the slab without chloride additions.

from behind the rebars [8]. Furthermore, there is a risk that the chlorides in these zones will be redistributed by diffusion after the treatment. At the end of the removal process on the second side the chloride profile becomes fairly uniform throughout the slab thickness.

Fig. 8a compares corrosion rates corresponding to slab areas in which ECR was performed on both sides and untreated areas, from the end of treatment until approximately 90 days later, a more than sufficient time to reach stable behaviour. Attention is drawn to the great similarity between the corrosion rates of the parts with and without ECR, and their notable difference to the $i_{\mathrm{corr}}$ values determined in the slab without chloride additions for similar degrees of wetness, which are included for comparative purposes. Fig. 8b shows the evolution of the potentials for identical situations. At the end of the removal process, for a very short time, the $E_{\mathrm{corr}}$ values become much more noble in the part where the treatment was carried out, compared with the potentials obtained in the same humidity conditions in the slab areas where chlorides were not removed; showing even less negative $E_{\mathrm{corr}}$ values than the slab without chloride additions.

Fig. 9 displays polarisation curves obtained for the slab with chlorides in an area where ECR was applied on both sides and for an untreated area, comparing both with the polarisation curve that shows the behaviour of rebars embedded in the slab without chlorides. As can be seen, irrespective of whether or not ECR has been performed, the curves for the different areas of the slab with chlorides are very similar, despite starting at very different $E_{\mathrm{corr}}$ values. The enormous difference between the current densities of the anodic branches of the two curves obtained for the slab with chlorides, in areas with and without ECR, and the densities of the curve corresponding to the slab without additives, indicates that the former correspond to the active state and the latter to the passive state, and that ECR in no way guarantees the repassivation of corroded rebars.

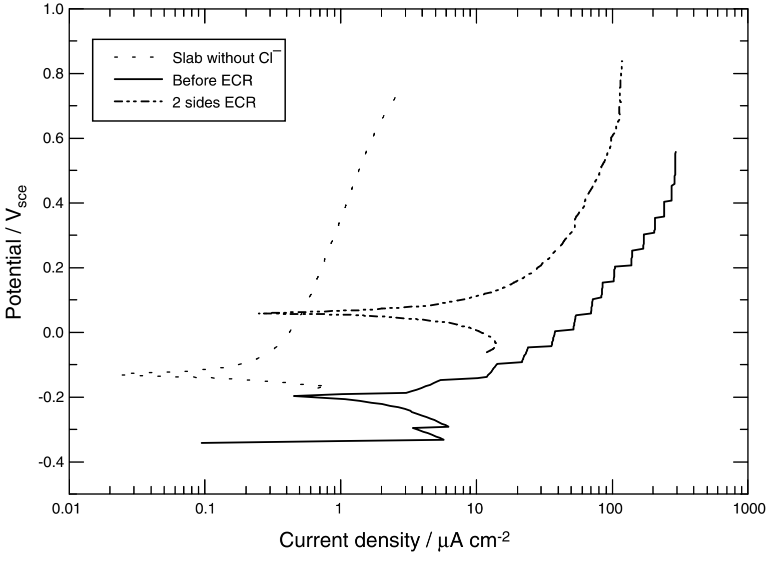

Fig. 9. Polarisation curves obtained on a slab area where ECR has not been performed and on an area where ECR has been performed on both sides. For comparative purposes, the polarisation curve for the slab without chloride additions is included.

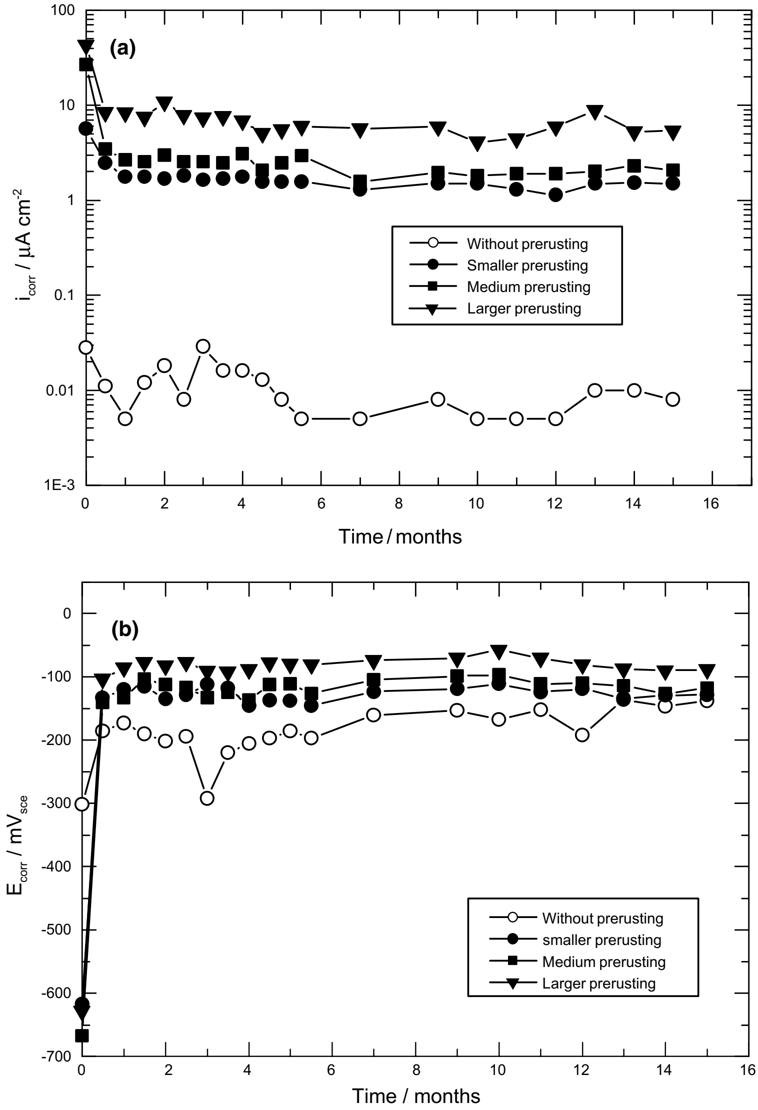

Fig. 10. Evolution with time of $i_{corr}$ (a) and $E_{corr}$ (b) values for electrodes with different precorrosion degrees embedded in small mortar specimens shown in Fig. 2.

As an example of the behaviour of clean and precorroded electrodes in cement mortar, Fig. 10a shows the $i_{corr}$ of plates with three different precorrosion degrees. The figure clearly illustrates the dependence that exists between the degree of prior attack and the corrosion rate, since higher precorrosion degrees show higher $i_{corr}$ values. Fig. 10b reveals a very uniform tendency of the corrosion potentials throughout the test, showing slightly more negative values the lower the precorrosion degree of the plates. Surprisingly, the $E_{corr}$ values of the passive (clean) electrodes are of the same order as the active (precorroded) electrodes, or even slightly more negative.

## 4. Discussion

### 4.1. Summary of questions and answers

On the basis of the results obtained, the questions posed in Section 1 can be answered in the following terms:

(1) *Is it possible to stop corrosion once it has started?*
Corrosion that has started can practically be halted by reducing the degree of saturation of the mortar or concrete's pore network until obtaining resistivities of $\geqslant 100\ \mathrm{k\Omega\,cm}$, which give rise, as can be seen in Fig. 5, to $i_{\mathrm{corr}}$ values of $\leqslant 0.1\ \mu\mathrm{A/cm^2}$, typical of the passive state, even in precorroded rebars [25]. However, this procedure is probably not feasible in many real structures. It can also be achieved by means of correctly applied CP, a method that is not analysed in the present study but which is capable of halting the corrosion of RCS irrespective of their chloride contents [6,7].

(2) *Can corroded RCS be repassivated?*
Since neither the uncarbonated and chloride-free mortar (Fig. 10) nor ECR from the slab with chlorides (Figs. 8a and 9) have proven to be capable of repassivating steel rebars with high or even moderate precorrosion degrees, it may be concluded that ERM cannot guarantee the recovery of the passive state of RCS already deteriorated by corrosion, even in ideal conditions (small mortar specimens without chlorides). Thus, an ECR process which removes a high percentage of chlorides, but not all (Fig. 7), can also not be expected to achieve the desired repassivation.

(3) *Are ERM for RCS effective; when?*
Both ERA and ECR may be considered to be effective prevention methods if applied before the carbonation front or the chlorides reach the rebar level. They may also be effective for repassivating steel with incipient corrosion degrees, as seems to be shown by previous results [11,26,27], but not as rehabilitation methods for RCS already deteriorated by corrosion (e.g. Figs. 8–10).

(4) *Is there a relationship between the precorrosion degree of rebars and the possibility of their repassivation?*
The higher the steel precorrosion degree, the greater its corrosion rate in chloride-free cement mortars (Fig. 10a) or in solutions that simulate the aqueous phase of the concrete pore network [26], and the lower the possibility of achieving its repassivation [26,28].

(5) *Is it sufficient to remove the causes of corrosion in order to halt the attack of corroded structures?*
ERM applied "at the right time" can be highly effective, i.e. if applied before the passive–active transition takes place, since it has been demonstrated that they realkalise the concrete [8–10] and substantially reduce the chloride level (Fig. 7). Applied preventively, ERM can prolong the corrosion initiation time indefinitely if used repeatedly, provided that the structure's chloride profile makes this advisable. Applied "at the wrong time", as corrective measures, they are ineffective (e.g. Figs. 7–10).

(6) *Can ERM be considered an end in themselves?*
Obviously not; a highly alkaline pH or the absence of chlorides does not offer any advantage in either aesthetic, safety or functional terms. If they are not able to

achieve the repassivation of corroded RCS—the only way of guaranteeing their durability, the use of ERM would be completely unjustified.

(7) *Can a simple potential measurement determine the active or passive state of rebars?*
As the $E_{corr}$ of rebars in a particular structural element can change by hundreds of mV depending on the saturation degree of the pores (Fig. 6), $E_{corr}$ values can be a valuable indicator but are insufficient on their own (if not considered in combination with the mortar or concrete's resistivity) to determine the active or passive state of the structure [25,26,28]. In electrodes embedded in mortar specimens similar potentials may correspond to $i_{corr}$ levels that differ by several orders of magnitude (Fig. 10), which means that this parameter on its own provides insufficient information on the corrosion rate in RCS.

(8) *Do corrosion rates measured before and after the application of ERM have the same meaning?*
All the parameters estimated by quantitative electrochemical techniques, i.e. $i_{corr}$ (Figs. 5, 8 and 10) and polarisation curves (Fig. 9), for clean and corroded electrodes adopt similar values before and after the application of ERM, typical of the passive state in the former case and the active state in the latter. The use of other quantitative techniques to estimate the corrosion rate, such as electrochemical impedance spectroscopy, or the direct measurement of the corrosion process time constant by the application of short duration galvanostatic or potentiostatic pulses, leads to similar conclusions [11,25,26]. We do not find any reason to suspect that the same methods measure different processes at different moments. In fact, they estimate with reasonable certainty the corrosion kinetics of precorroded steel in a $Ca(OH)_2$ saturated solution, according to our own results [26,27] and in reinforced concrete specimens according to the experience of Novak et al. [29,30].

(9) *Do chlorides continue to be necessary for corrosion to continue once it has started?*
The $i_{corr}$ values habitual in RCS corroding in active state seem sufficient to maintain an acid pH at the steel/corrosion products interface inside a highly alkaline medium like concrete [26,28], and so the complete removal of $Cl^-$ does not guarantee the repassivation of corroded rebars, as is corroborated by the results of this research in mortar without chlorides (Fig. 10); and much less when the removal of chlorides is partial, as occurs when ECR is applied to structural elements (Figs. 7–9).

### 4.2. Some additional considerations about ERM

At times it is doubted whether $R_p$ measurements in the steel/concrete system provide a correct indication of the $i_{corr}$, due to the presence of electrochemical reactions that are unrelated with metal corrosion [1,31], such as the reaction between ferrous and ferric ions:

$$Fe^{3+} + 1e^- \Longleftrightarrow Fe^{2+} \tag{1}$$

with an equilibrium potential:

$$E = 0.771 + 0.0592 \log[Fe^{3+}]/[Fe^{2+}] \tag{2}$$

since when the dissolved oxygen is removed from the $Ca(OH)_2$ solution by deaerating with nitrogen, the cathodic current is barely reduced in the presence of chlorides. Nevertheless, the $E_{corr}$ values determined in the present research (Figs. 6, 8 and 10) are too negative to significantly interfere with this equilibrium.

We consider it to be sufficiently demonstrated that oxygen, which is indispensable for the initiation of the corrosion process in the active state, ceases to be necessary once the passivating layers have been broken [32,33]. In the presence of chlorides a concentrated solution with ferrous chloride ions is produced at the local anodes, whose equilibrium pH is situated around 5 [33]. The cathodic process becomes the reduction of protons, even in a medium with a bulk pH as basic as concrete, and can proceed without oxygen.

$R_p$ measurements integrate the electrode processes and it may be considered, in a similar way to that proposed for the atmospheric corrosion of steel, that the metal dissolution process involves the contribution of several partial cathodic processes [34]:

$$i_{\text{Fe-diss}} = i_{\text{oxygen-red}} + i_{\text{oxid-red}} \tag{3}$$

which, in the presence of chlorides or in carbonated concretes, must include the participation, at least in some areas of the surface, of the reduction of hydrogen:

$$2H^+ + 2e^- = H_2 \tag{4}$$

with a potential that becomes 59 mV nobler with each unit decrease in the pH:

$$E = 0.00 - 0.0592\text{pH} - 0.0296 \log P_{H_2} \tag{5}$$

The metal dissolution process in RCS which have lost their passive state very probably involves a significant contribution of the latter partial cathodic process, which explains why passive steel often exhibits $E_{corr}$ values that are similar to or even more negative than the $E_{corr}$ of precorroded electrodes (Fig. 10b).

$$i_{\text{Fe-diss}} = i_{\text{oxygen-red}} + i_{\text{oxid-red}} + i_{\text{hydrogen-red}} \tag{6}$$

We therefore consider that $R_p$ measurements, especially in the case of precorroded electrodes, reflect a complex corrosion process like that described by Eq. (6) rather than the exchange current of an equilibrium. Furthermore, if the exchange current of an equilibrium is measured, the apparent $i_{corr}$ would increase greatly for the $E_{corr}$ closest to the characteristic potential of that equilibrium, while the experimental data shows: (a) That precorroded electrodes show high corrosion rates which are very similar for potentials that differ by hundreds of mV, while clean electrodes, also in a very wide range of potentials, exhibit much lower corrosion rates [26]. (b) On the contrary, despite having very similar potentials, the two types of electrodes give rise to completely different behaviour (Fig. 10).

During the application of ECR the rebars are subjected to high negative potentials, initially approximately −7 V and rising to almost −40 V in the final days of extraction, due to the progressive elimination of the chlorides and decrease in the mortar's conductivity. Studies currently under way show that these potentials almost completely reduce ferric compounds to magnetite, changing the appearance of the corrosion products that surround the rebars from a reddish colour to dark brown.

The reduction of the corrosion products to ferrous compounds by ECR would mean that the $i_{\text{oxid-red}}$ in Eqs. (3) and (6) would be insignificant. Due to the depassivating effect of the extraction treatment [19], after ECR the evolution of hydrogen could be the main cathodic reaction in large areas of the rebars. This possibility would be favoured by the concurrence of chloride ions, which have not been completely removed (Fig. 7), and ferrous ions, which would produce local areas of a considerably lower pH than the bulk pH of the mortar.

### 4.3. Possible future work

Our intention has been to find the answers to a series of concerns about the efficiency of ECR in RCS damaged by corrosion; a highly suggestive and important matter which continues to arouse controversy. At the present time we are trying to specify the effects of ECR on steel corrosion products, the permeability of the mortar and the microstructural changes that take place in the latter, following the valuable contributions of other authors [17–20]. We also consider it to be interesting to analyse in future research:

(a) To what point the Stern and Geary equation [35] allows a sure estimate of the progress of corrosion in RCS that have already undergone the transition from passive to active state, comparing electrochemical estimates of corrosion with its direct measurement by gravimetry. It would be necessary to start with very well defined prerusting grades in order to be able to accurately measure the additional corrosion that subsequently takes place in the mortar or concrete. Novak et al. [29,30] reach different values for the constant $B$ depending on whether the concrete is contaminated with chlorides or not and whether the rebars are prerusted or not. In concordance with our results, the prerusted steel is not repassivated even in chloride-free mortar.

(b) The causes of the great ennobling of the $E_{corr}$ in the slab area where ECR was performed, by around 500 mV (Fig. 8b), for which no convincing explanation is found. This may perhaps be due to an increase in the porosity of the mortar due to the effect of the high current densities used, which would facilitate the oxygen saturation of the aqueous phase of the pores and, with this, the increase in $E_{corr}$. It should be pointed out that this ennobling of $E_{corr}$ values, which is often presented as "proof" of the repassivation of corroded RCS, has not led to any beneficial effect on the $i_{corr}$ (Fig. 8a).

(c) Whether the proportionality between the $i_{corr}$ and the mass of the corrosion products existing on the surface of the steel electrodes, verified in a $Ca(OH)_2$ saturated solution used to approximately simulate the aqueous phase of the concrete pore network [26], is reproduced in the mortar. If the proportionality is maintained, the sum of the partial cathodic reactions in Eq. (6) would be determined by the surface development of the corrosion products and would be an additional demonstration that ECR is a preventive but not a curative method.

## 5. Conclusions

(1) It is possible to halt corrosion that has been initiated in RCS, achieving $i_{corr}$ values of $\leqslant 0.1\ \mu A/cm^2$, typical of the passive state, by sufficiently reducing the degree of saturation of the concrete pore network. However, $i_{corr}$ values will shoot up again in periods of rainfall or high RH.

(2) From the results obtained it can be stated that the repassivation of steel surfaces with medium or high precorrosion degrees is not possible.

(3) The greater the steel precorrosion degree, the higher the rate of its attack in chloride-free cement mortars.
(4) ERA and ECR are able to remove the causes of corrosion, but this is not sufficient to halt the corrosion process if the RCS is already in an active state.
(5) Neither the phenolphthalein test, the determination of chloride profiles, or the simple measurement of potentials before and after the application of ERM can guarantee the efficiency of the latter, and it is necessary to use techniques that provide quantitative determinations of the corrosion kinetics.
(6) Both ERA and ECR can be considered effective prevention methods, if they are applied before the carbonation front or chlorides reach the rebar level, but not as rehabilitation methods for RCS already deteriorated by corrosion.

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