A contribution to the rehabilitation of reinforced concrete structures by non-destructive electrochemical methods

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Abstract

The aim of this work has been the study of an electrochemical treatment that allows the prevention and halting of chloride corrosion processes in passive reinforced concrete. This treatment is based on a desalination system that removes free chloride in concrete simultaneously increasing the pH around reinforcement steel until its repassivation.

With this purpose a concrete has been manufactured with mixing proportions close to that used in civil engineering. The chloride attack has been carried out at room temperature, and the chloride removal process has been started at several concrete ages. Chloride ions have been determined before and after the attack, as well as the corrosion potential, in order to establish comparison between the grade of corrosion of the reinforcement steel before and after treatment, according to exposition time and initial corrosion situation. Relationships between electrochemical parameters have been determined.

The studied procedure is a non-destructive and non-intrusive method that does not change either the strength of the concrete or its external appearance. The procedure uses non-pollutant materials, so no environmental damage is caused.
Keywords: electrochemical chloride extraction, steel-reinforced concrete, repassivation.

1 Introduction

Corrosion in steel reinforcement caused by exposition to chlorides is the main cause of deterioration in steel-reinforced concrete structures. Electrochemichal

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chloride extraction (ECE, also named desalination) is a method to repair steel reinforced structures that have suffered chloride attack [1, 2], although it can be also applied as a prevention treatment [3].

The treatment consists of the application of an electric current between the steel, acting as a cathode, and a temporary external anode placed on the concrete surface. As reported by Arya *et al*. [4], chloride removal increases with increasing applied potential, number of reinforcing bars at a particular depth and initial chloride content, although chloride remaining seems to be independent of the initial chloride content. This method requires the chloride ions to be in the pore water to be transported out of the concrete [2]. Removal of 40 to 70% of the initial chloride has been observed using this technique [1, 5, 6]. On the other hand, repassivation of steel due to the increase in the potential of corrosion after the chloride removal has been studied by several authors [5, 6, 7].

In this work, electrochemical chloride removal has been studied on reinforced concrete that has been subjected to different degrees of corrosion. The measurement of the potential of corrosion has allowed the probability of corrosion to be determined before and after the treatment according to these values for the potential [8]:

- Higher than -200 mV: low probability (0-5%)
- Between -200 and -350 mV: medium probability (5-50%)
- Lower than -350 mV: high probability (50-100%)

Finally, the time period during which the treatment should be maintained to ensure the rehabilitation of concrete has been studied.

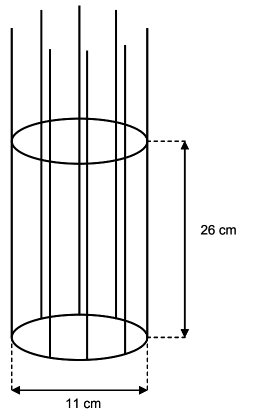

Figure 1: Disposition of the reinforcement steel in the test specimens.

2 Materials and methods

2.1 Production of tests specimens

40 cylindrical standard test specimens were cast and molded according to UNE EN 83301:91 (150 mm in diameter and 300 mm in length). 33 of the specimens were reinforced with eight steel bars (AEH-400) connected by two circular fences as it is shown in fig. 1. The steel surface was mechanically cleaned before

use. In order to accelerate the corrosion process, 2 cm of covering layer was selected to cover the steel bars. This must not affect the results, since the goal of this work is a comparative study between several corrosion and regeneration conditions. The concrete composition, shown in table 1, corresponds to a typical mixing for building purposes. Steel characteristics are also shown in table 1.

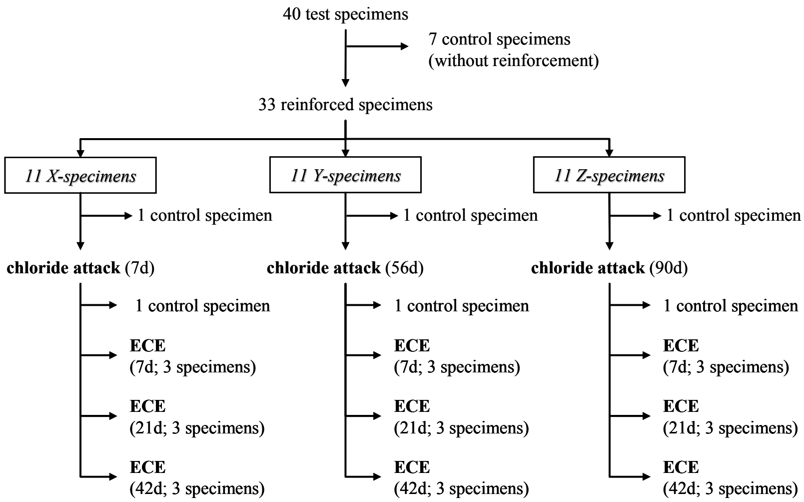

Figure 2: Schedule followed for the experiment.

Test specimens were compacted in a shaking table and demolded after 24 hours. Then, they were maintained in a wet room for six days. After this period, they were subjected to chloride attack and electrochemical treatment following the schedule shown in fig. 2.

2.2 Chloride attack

Chloride attack was carried out in two pools of 350 l, containing a solution with 150 g $NaCl \cdot l^{-1}$ (52 g $Cl^{-} \cdot l^{-1}$). Water evaporation was controlled, maintaining chloride concentration within a ±2% variation.

2.3 Electrochemical chloride extraction treatment

In order to save time, the treatment for chloride removal was applied to batches of nine specimens at a time. A current intensity of 1 $A \cdot m^{-2}$ with a potential of 20 V was supplied and maintained constant during the required period of time. Fig. 3 shows the electrochemical chloride extraction system for a specimen. A first 2 cm layer of wet cellulose paste covered the specimen. This layer acts as an exchange electrolyte between reinforcement bars and a titanium anode mesh. Finally, the whole system was coated with a second 1.5 cm wet cellulose layer in order to maintain the wet conditions.

2.4 Potential measurements

Corrosion potentials were measured using an *in situ* measurement system "Colebrand" with a $Cu/CuSO_4$ reference electrode.

Table 1: Concrete composition and steel characteristics.

Concrete	
Cement CEM I 42,5R	346 kg/m^3
Calcareous Sand 0/5	1289 kg/m^3
Calcareous gravel 5/12	521 kg/m^3
Calcareous gravel 12/18	739 kg/m^3
Water	225 L/m^3
w/c	0.65
Compressive strength 28d	45 MPa
Steel bars AEH-400N	
Diameter	3 mm
Modulus of elasticity	4100 kp/cm^2
Breaking stress	4500 kp/cm^2

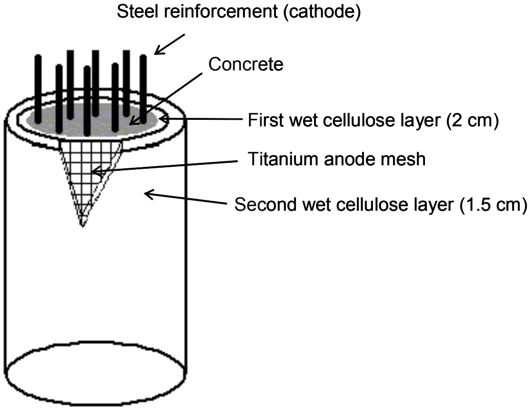

Figure 3: Electrochemical extraction system.

3 Results and discussion

For a better monitoring of the corrosion and electrochemical removal processes, the corrosion potential was measured in two points of each of the two bars which constituted the reinforcement structure, at 1/3 and 2/3 height from the specimen basis. The measurements were taken before and after electrochemical treatment. Table 2 shows the increase in the potential of corrosion in each set of specimens produced by the chloride attack.

3.1 X-specimen set (7 day chloride attack)

The attack on this set was a low intensity attack, simulating an initial stage of corrosion or a concrete with an excess of chloride. Fig. 4 shows the evolution with time of the potential of corrosion for this set. As it can be seen in the table 3, the corrosion potential decreases a 28.3% during the first week of the chloride removal treatment. From the second week to the end of treatment, the reduction in the corrosion potential was about 6-7% per week. The total decrease with respect to the initial corrosion potential was 60.2% (from -283 mV to -112.7 mV).

For this set, the first week of treatment caused a reduction in the potential of corrosion enough to reach the low corrosion probability zone, as it is shown in fig. 4. This is due to the fact that the corrosion process was hardly initiated after 7 days to chloride exposition, and chloride ions had not penetrated deeply into concrete. Consequently, chloride removal was carried out quickly.

From these results, it can be concluded that a four week removal treatment would be enough for structures with a low corrosion degree.

Table 2: Increase in the potential of corrosion for each set after attack.

	X-specimen set (7 day attack)	Y-specimen set (56 day attack)	Z-specimen set (90 day attack)
Potential before attack (mV)	-110	-110	-110
Potential after attack (mV)	-283	-524	-621
Variation (%)	157	376	464

Table 3: Decrease of the potential of corrosion for each set after treatment.

	X-specimen set (7 day attack)	Y-specimen set (56 day attack)	Z-specimen set (90 day attack)
Decrease 1st week of ECE	28.3	13.3	17.1
Decrease (per week) after 3 weeks of ECE	5.84	12.6	10.9
Decrease (per week) after 6 weeks of ECE	6.73	9.38	8.90
Cumulative decrease 1st week of ECE	28.3	13.3	17.1
Cumulative decrease after 3 weeks of ECE	40.0	38.6	34.8
Cumulative decrease after 6 weeks of ECE	60.2	66.7	61.6

3.2 Y-specimen set (56 day chloride attack)

The attack on this set was a medium-high intensity attack, simulating a concrete with a corrosion degree such that the structure is damaged, but not in a way to be at risk for the moment. Fig. 4 shows the evolution with time of the potential of corrosion for this set. As table 3 shows, the reduction of the potential of corrosion for this set is maintained between 9 and 13% per week, decreasing with a regular rate along the period of time in which the experiment was carried out. The total decrease with respect to the initial corrosion potential was 66.7% (from -523.8 mV to -174.3 mV).

For this set, the low corrosion probability zone was reached after six weeks of treatment, although a few more weeks could be necessary to ensure the concrete to stay in this low risk zone.

From these results, it can be concluded that a ten or eleven week removal treatment would be needed to ensure a correct rehabilitation of structures with a medium or high degree of corrosion.

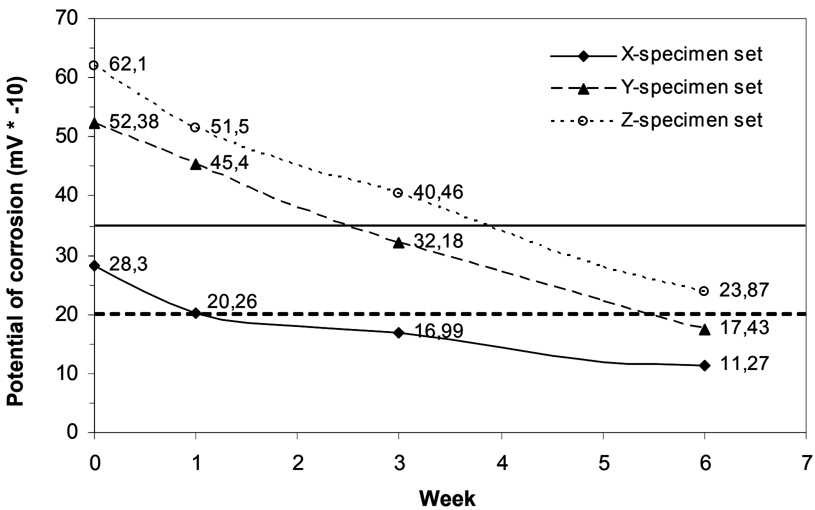

Figure 4: Evolution of the potential of corrosion during the electrochemical removal of chloride. Horizontal line: 50% probability of corrosion. Horizontal plotted line: 5% probability of corrosion.

3.3 Z-specimen set (90 day chloride attack)

The attack on this set was a high intensity attack, simulating a very damaged concrete, which would imply its demolition if it was a structural concrete. Fig. 4 shows the evolution with time of the potential of corrosion for this set. As it is shown in table 3, the reduction per week of the potential of corrosion for this set decreases with time from 17.1% to 8.90%. The total decrease with respect to the initial potential of corrosion was 61.6% (from -621 mV to -239 mV).

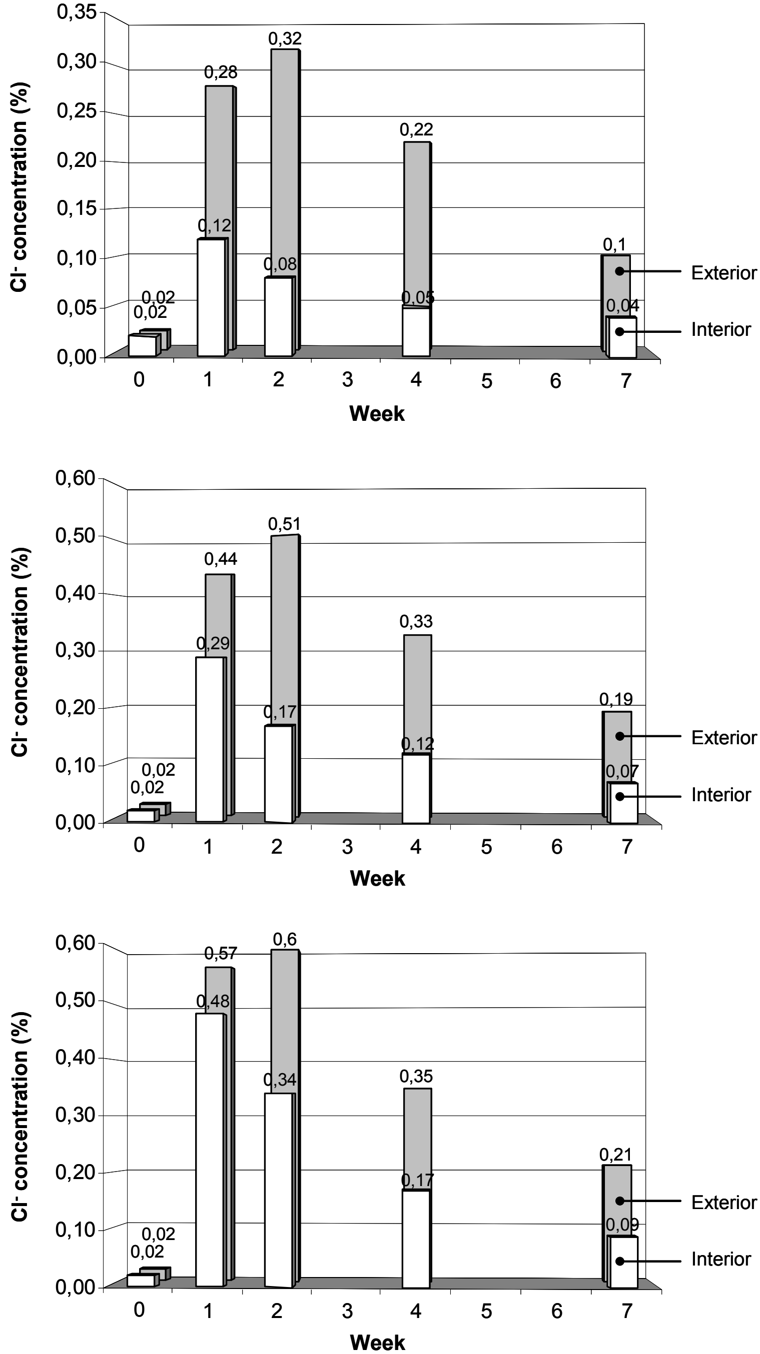

Figure 5: Evolution of chloride concentration inside and near surface.

For this set, after six weeks of electrochemical removal, the zone of medium risk of corrosion (5-50% probability) is reached. An extrapolation of the data obtained for this set, showed that 12 weeks of treatment would be needed to reach the low risk of corrosion zone for the rehabilitation of highly damaged concrete elements.

3.4 Evolution of chloride concentration

Chloride concentration was monitored both inside the test specimens (near reinforcement) and near the surface of the specimen. Results for the three sets are pictured in fig. 5.

Chloride concentration decreased between 65 and 71%, and the results were in concordance with that obtained from the study of the potential of corrosion, supporting the conclusions previously drawn.

4 Conclusions

After electrochemical removal treatment, chloride concentration decreased between 65% and 71% in the three sets of specimens studied. The potential of corrosion decreased about 60% in all cases, lowering the probability of corrosion to less than 5% for specimens subjected to low and medium intensity chloride attack.

Depending on the degree of the aggression by chloride ions, between 4 to 12 weeks of electrochemical treatment can be needed to ensure a correct rehabilitation of concrete.

The results obtained have shown that electrochemical chloride removal is a useful technique for rehabilitation of reinforced concrete structures subjected to corrosion of steel reinforcement by chloride attack.

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