

## CAN LOCAL REPAIRS BE DURABLE SOLUTIONS FOR STEEL CORROSION IN CONCRETE STRUCTURES?

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### ABSTRACT

The loss of the natural protection given by the concrete cover may occur due to many mechanisms, particularly carbonation and ingress of chlorides. Usually, in both cases, the whole structural element is attacked, however corrosion manifests typically only at localized areas.

The localized repair of the corroded area normally requires removing the damaged concrete, cleaning the reinforcement, and casting mortar or microconcrete to recover the original cross section of the structural element. The objective of the majority of the available repair systems is only to protect the repaired area, however this may originate the transfer of the corrosion cell. To study this topic, a research program was developed to analyze the performance of the following repair systems: mortar, polymer modified cement paste paint applied to the steel, epoxy coating on the steel surface, corrosion inhibitor admixture added to the reference mortar, and microsilica based admixture added to the reference mortar. The study was performed using reinforced concrete beams (15x15x60 cm) subjected to semi-immersion in sodium chloride for one year. The damage was determined by measuring the corrosion potential (ASTM C876), carbonation depth (RILEM CPC 18), amount of chlorides (ASTM C1152), visual observations, and loss of mass (ASTM G1). The transfer of corrosion cell was observed and the repair systems had significant different performance.

**Keywords:** calcium nitrite, carbonation, calcium chloride, corrosion, concrete durability, epoxy paint, mortar, polymer, repair, silica-fume, testing.

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## INTRODUCTION

The evidence of corrosion in reinforced concrete members typically appears in localized areas. It is common practice to remove the damaged concrete, clean the reinforcement, and subsequently cast mortar or microconcrete to recover the original cross section of the structural element. The objective of most of the available repair systems is to protect the repaired region, however this may originate the transfer of the corrosion cell. The purpose of this paper is to develop a methodology to evaluate the performance of materials and systems of localized repair in structures with corrosion problems. A research program was developed to analyze the performance of the following repair systems: mortar, polymer modified cement paste paint applied to the steel, epoxy coating on the steel surface, corrosion inhibitor admixture added to the reference mortar, and microsilica based admixture added to the reference mortar. The study was performed using reinforced concrete beams (15x15x60 cm) subjected to semi-immersion in sodium chloride for one year. In addition to the corrosion potential (ASTM C876), the chloride content at different depths was also determined (ASTM C 1152 ) to measure the movement of chloride ions migration in the electrolyte as a function of the electric fields generated by the corrosion cells. The carbonation depth, determined by the RILEM CPC 18 method, was measured to evaluate the effects of the carbonation process in the liberation of chlorides of Friedel's salts (calcium chloro-aluminates). After one year of testing, the prismatic specimens were split, photographed and observed in detail. A record of the extent of corrosion of each specimen was made. After that, the bars were cleaned and weighed according to the ASTM G 1 , and thereby, the total mass loss of the main steel bars was obtained.

## TESTING PROGRAM

### **Repair and measurements**

The size and location of the repaired region, as well as the location of the reference electrodes used to measure the corrosion potentials are shown in Figure 1. The repairs were performed after corrosion had started, between two to three months after casting the specimens.



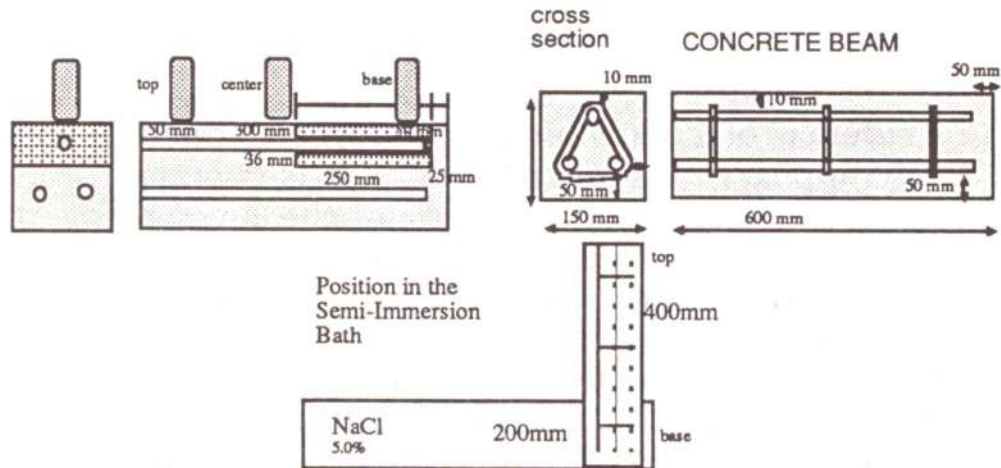


Figure 1 - Schematic representation of the size and location of the repaired regions, as well as the position of the reference electrodes used for measurement of the corrosion potentials (ASTM C 876).

### Materials

ASTM A 615 Grade 60 laminated steel bars with nominal diameter of 12.7 mm and stirrups of 4 mm in diameter were used.

ASTM Type II Portland cement was used with the following potential composition:  $C_3S = 57.5\%$ ,  $C_2S = 19.80\%$ ,  $C_4AF = 11.20\%$ , and a specific mass of  $3120 \text{ kg/m}^3$ .

Natural siliceous river sand meeting ASTM C 33 was used as the fine aggregate with a maximum size of 2.4 mm, fineness modulus of 3.1, bulk specific gravity of  $2640 \text{ kg/m}^3$ , and water absorption of 1.45 % .

Natural siliceous river gravel meeting ASTM C 33 was used as the coarse aggregate with the following basic mineralogical composition: metagraywacke (32 to 38%), graywacke (21 to 23%), chert (11 to 18%), metabasic igneous (13 to 16%), quartz veins (8 to 10%), granitic, meta-volcanic quartzite ( 1 to 5%), and serpentine (1 to 2 %). It had maximum size of 19 mm, fineness modulus of 5.88, specific mass of  $2640 \text{ kg/m}^3$  and water absorption of 0.34 % .

One percent of calcium chloride by weight of cement was added to the concrete mixture with the objective of accelerating the corrosion process. Table 1 presents the composition and characteristics of the reference concrete.

TABLE 1. Composition and Properties of the Reference Concrete

Concrete	Description	Remarks	
composition	cement		305 kg / m <sup>3</sup>
	fine aggregate	sand	951 kg / m <sup>3</sup>
	coarse aggregate	gravel	912 kg / m <sup>3</sup>
	water		198 kg / m <sup>3</sup>
	Calcium Chloride		2.16 kg / m <sup>3</sup>
fresh concrete	entrapped air (sand+gravel)/cement		0.61 %
	w/c		6.11 kg / kg
	slump		0.65 kg / kg
	unit weight		50±10 mm
			2368 kg / m <sup>3</sup>
hardened concrete	compressive strength ASTM C 39	7 days	26.6 MPa
		28 days	32.1 MPa
		63 days	37.8 MPa
		1 year	40.7 MPa
	chloride penetration ASTM C 1202	7 days	11.500 C
		28 days	8.530 C
		63 days	6.420 C
		1 year	4.400 C
	porosity ASTM C 642	7 days (void vol. / total vol. )	11.4 %
		28 days (void vol. / total vol. )	9.6 %
		63 days (void vol. / total vol. )	9.4 %
		1 year (void vol. / total vol. )	9.0 %
	carbonation RILEM CPC 18	(38±1)°C R.H (65±5)%	≤ 8 mm

### Repair Materials

- The reference repair mortar was prepared with the same cement and sand used to prepare the reference concrete, but without salt additions. Table 2 shows the mixture proportions of the fresh and hardened mortar.
- Cement based polymer modified paint was applied directly on the surface of the bars.
- Epoxy paint was applied directly to the surface of the reinforcing bars.
- Calcium nitrite-based corrosion inhibitor (liquid) was added to the repair mortar as a chemical admixture. The reference mortar containing this admixture had properties equivalent to those of the repair mortar (see Table 2), with exception to the chloride penetration values which decreased to 2360 C at 28 days and to 2140 C at 300 days.
- Silica-fume based admixtures were added to the repair mortar. Care was taken to properly homogenize the admixture into the repair mortar. The reference mortar containing this admixture had a chloride penetration value of 320 C at 28 days and of 325 C at 300 days. The compressive strength increased to 60.3 MPa at



28 days and to 66.7 MPa at 300 days. The porosity decreased to 8.8% at 28 days and to 7.1% at 300 days. The carbonation depth was equal or less than 4 mm on the top position.

Table 2 - Composition and characteristics of the reference mortar

Mortar	Description	Remarks	
Composition	cement	sand	692 kg / m <sup>3</sup>
	fine aggregate		1385 kg / m <sup>3</sup>
	water		243 kg / m <sup>3</sup>
fresh mortar	entrapped air		1.27 %
	sand / cement		2.0 kg / kg
	w/c		0.35 kg / kg
	slump		120±20 mm
	unit weight		2320 kg / m <sup>3</sup>
hardened mortar	compressive strength ASTM C 39	28 days	51.6 MPa
		300 days (10 months)	59.8 MPa
	chloride penetration ASTM C 1202	28 days	4.350 C
		300 days (10 months)	2.830 C
porosity ASTM C 642	28 days (void vol. / total vol. )	12. %	
	300 days (void vol. / total vol. )	10.6 %	
carbonation RILEM CPC 18	(38±1)°C R.H (65±5)%	≤ 3 mm	

## Repair systems

### System I - reference mortar

The perimeter of the region to be repaired was cut with a cutting saw and the concrete removed to a depth of 2 cm below the steel. The corrosion products were cleaned with water and steel brush. The substrate was saturated with potable water, the forms put into place, and the region filled with well-vibrated mortar, and then the specimens were wet cured.

### System II - polymer modified cement paste paint

The perimeter of the region to be repaired was cut with a cutting disc and the concrete removed to a depth of 2 cm below the steel. The corrosion products were cleaned with water and steel brush, and with a cloth wet in acetone. After 20 minutes, three layers of paint were applied with a paint brush with a 15 minutes interval between the application of each layer of paint. The components of the mixture were previously mixed manually for at least 3 minutes to obtain a homogeneous mixture. After the paint had dried up, the repair mortar was carefully applied. The forms

were put into place, and the region filled with well-vibrated mortar, and then the specimens were wet cured.

#### **System III - epoxy-based paint**

The perimeter of the region to be repaired was cut with a cutting disc and the concrete removed to a depth of 2 cm below the steel. The corrosion products were clean with water and steel brush, and with a cloth wet in acetone. After 20 minutes, one layer of paint was applied with a paint brush. The repair mortar was carefully applied (after about 15 minutes) before the paint had dried up to guarantee adherence. The forms were put into place, and the region filled with well-vibrated mortar, and then the specimens were wet cured.

#### **System IV - corrosion inhibitor admixture added to the mortar**

The perimeter of the region to be repaired was cut with a cutting disc and the concrete removed to a depth of 2 cm below the steel. The corrosion products were cleaned with water and steel brush. The repair mortar was applied with the admixture in the following proportion: 4.5% of liquid admixture by mass of cement. The substrate was saturated with potable water, the forms put into place, and the region filled with this well-vibrated repair mortar, and then the specimens were wet cured.

#### **System V - microsilica-based admixture added to the reference mortar**

The perimeter of the region to be repaired was cut with a cutting disc and the concrete removed to a depth of 2 cm below the steel. The corrosion products were cleaned with water and steel brush. The substrate was saturated with potable water, the forms put into place, and the region filled with this well-vibrated repair mortar, and then the specimens were wet cured.

## **RESULTS**

At the end of the experimental evaluation, the beams were split for visual observation and measurement of the mass loss. The results from the visual observations are presented in Fig. 2. For the determination of mass loss, the bars were cleaned through several cycles of immersion in a solution of 500 ml of hydrochloric acid, 3.5 g of hexametileno tetramina, and distilled water to complete 1,000 ml. Each cycle of immersion in solution lasted for 10 minutes. After immersion in solution, the bars were immersed in distilled water and their weights measured. This process was repeated until constant weight was achieved, that is, a difference of less than 3/100 of a gram after two consecutive



measurements. This process satisfactorily cleaned the bars removing not only the corrosion products but also small fragments of adhered mortar (ASTM G1). Table 3 shows the loss of mass results for the five repair systems.

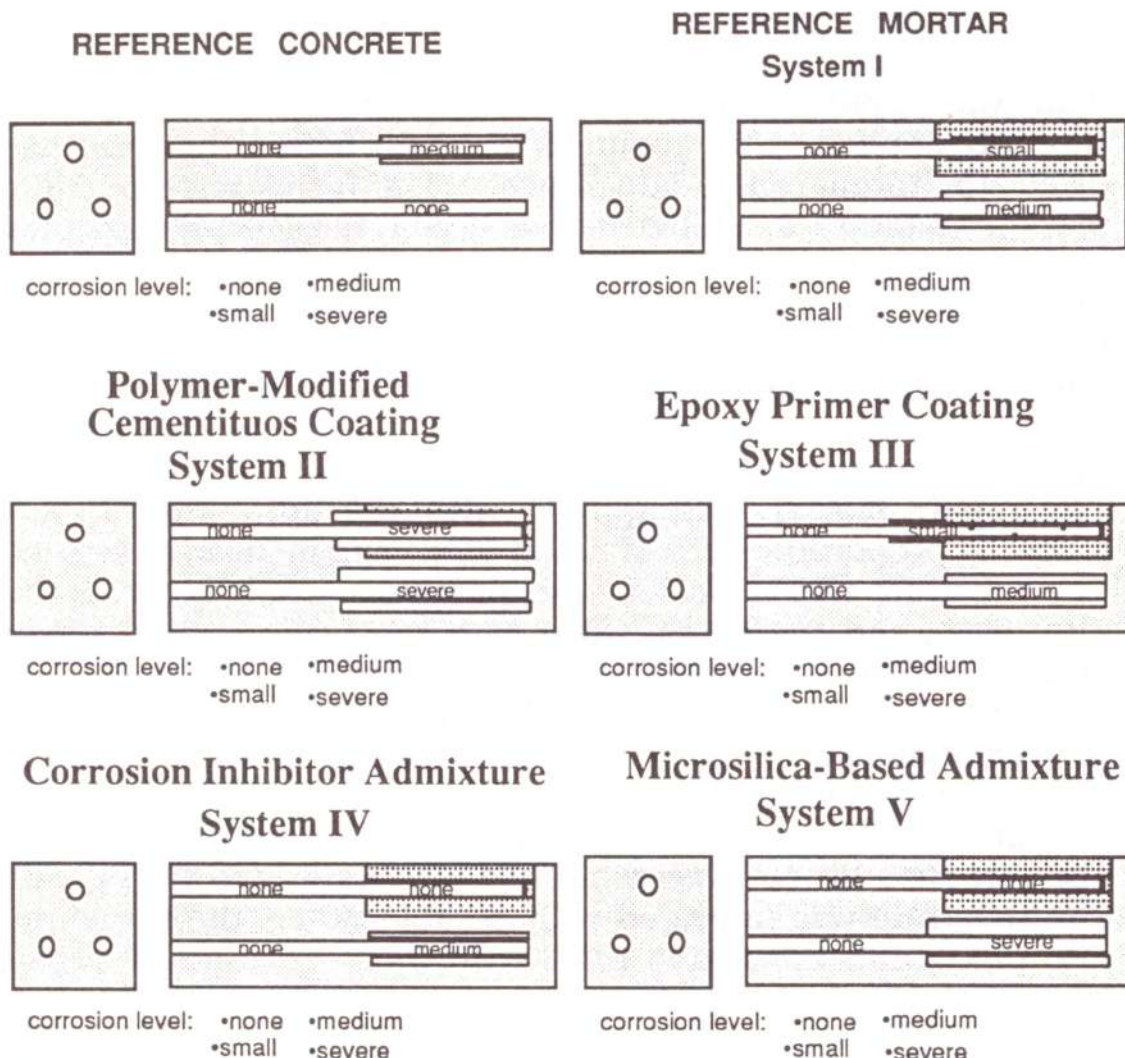


Figure 2 Extent of corrosion in prismatic specimens repaired with different system

Table 3 - Loss of mass after one year (average values obtained from testing 5 specimens).

Bar	Reference Concrete	System I	System II	System III	System IV	System V
	not repaired	repaired	repaired	repaired	repaired	repaired
main	0.606	0.223	0.681	0.125	0.005	0.006
left	0.004	0.548	0.655	0.552	0.571	0.691
right	0.004	0.528	0.683	0.538	0.533	0.709

0,050  
0,060

The results for corrosion potential are shown in Figure 3. Samples for chloride content were taken at different depths in the specimens with a dry core driller. The powder material was analyzed for chloride content according to ASTM C 1152. The chloride content (percentage of  $\text{Cl}^-$  by mass of cement) at several depths in each of the repair systems is shown in Table 4.

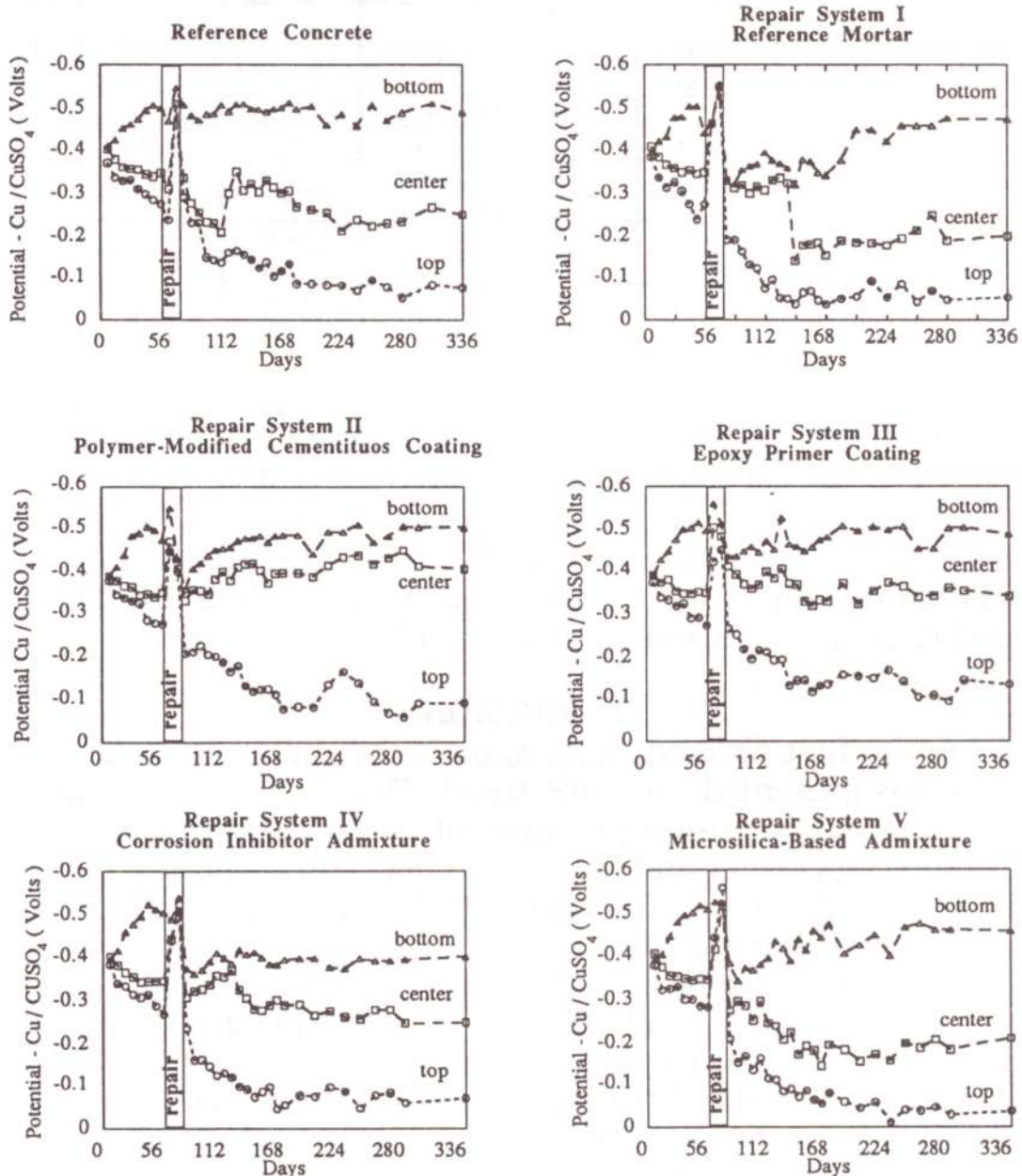


Figure 3 - Corrosion potential (ASTM C 876) obtained with several systems, with relation to the main bar (depth of cover = 1 cm, period of time = 1 year, potential values in Volts). Note the period of repair.



Table 4 - Chloride content (ASTM C 1152) at different depths.

Position	Depth mm	Reference Concrete	System I	System II	System III	System IV	System V
		not repaired	repaired	repaired	repaired	repaired	repaired
T O P	0 to 5	0.420	*	0.411	*	0.368	0.393
	5 to 10	0.414	0.407	*	0.402	0.424	*
	10 to 15	*	0.374	0.367	0.378	*	0.418
	20 to 25	0.406	*	0.388	*	0.369	0.389
	30 to 35	0.386	0.400	*	0.405	0.384	*
	45 to 50	*	0.372	0.406	0.363	*	0.395
B O T T O M	0 to 5	0.934	0.395	0.410	0.412	0.304	0.215
	5 to 10	0.947	0.332	0.346	0.314	0.151	0.096
	10 to 15	0.521	0.530	0.581	*	0.539	0.545
	20 to 25	0.407	0.408	0.412	0.402	0.387	0.430
	30 to 35	0.395	*	0.411	0.421	0.376	0.397
	45 to 50	0.403	0.552	0.567	0.510	0.531	0.548

\* not tested

Carbonation did not occur in the submerged region. In the region of contact with the ambient (R. H = 65 ± 5% and T = 38 ± 1 °C), the increase in the carbonation depth ( $e_x$ ) followed the law  $e_x = k t^{1/2}$ . The value of  $k$  was 5.8 mm.year<sup>-1/2</sup> for an observation period of one year (1.6 mm.year<sup>-1/2</sup> for a 28-day period). The carbonation depth was determined with a phenolphthalein-based chemical indicator (RILEM CPC 18).

## DISCUSSION

During the first 63 days, that is, until the repair age all tested specimens presented the same trend (Fig. 3). The 32 specimens had an initial corrosion potential of about -0.4 V in the three positions: top, center and bottom. In the central and top regions, the potential increased progressively until the repair date, showing the depassivation of the bars in these regions. As expected, the potential decreased in the bottom portion, showing that the geometric configuration of the specimens and the immersion procedures were adequately selected to induce corrosion in a localized region at the interface air/solution. After the repair work in the affected region was performed and the specimens were re-introduced into the chloride solutions, a distinct behavior was observed for each repair system. The main steel bars in the reference concrete, reference mortar, and systems IV and V were maintained approximately passivated in the top and central regions; whereas systems II and III had potentials which are characteristics of depassivation in the



central region. Nonetheless, in the bottom region all of them had potentials values characteristic of corrosion.

This indicates that the evaluation criteria suggested by the ASTM C 876 should be used with caution. These criteria were established based on the results obtained by Stratfull<sup>6,7</sup> in the 70's for bridge decks with corrosion typically caused by deicing salts. Elsener and Bohni<sup>8</sup> pointed out that the values obtained based on these criteria should be used only as reference. These reference values can provide useful information when used in combination with other properties such as chloride content, concrete resistivity, and depth of carbonation. Babaei<sup>9</sup> reported the positive experience of using this method in more than nine State Transportation Departments in the USA and England. He also presented results showing the reproducibility and repeatability of the test performed with two different equipments at the same location and with one equipment applied at the same points for more than 5 times.

In the present experimental study conducted in 32 specimens molded using the same procedures and subjected to identical exposure conditions until the repair age, the standard deviation for the test was 0.026 V, with a total average variability, expressed by the coefficient of variation, of only 7%. The results were randomly distributed and independent of the extent of corrosion of the bars, that is, passive or active. These results demonstrate that the method is reliable since the coefficient of variability is lower than that normally accepted for the uniaxial compression test of concrete specimens.

Considering that the magnitude of the potential difference between nearby regions can be used as an indication of the extent of corrosion, and taking the potential difference between the top and the bottom regions as reference, it can be inferred from Figure 4, that the systems II and III appear to present high rates of corrosion. Visual observation and determination of mass loss (Table 3) have confirmed this inference. Visual observations also indicated that the main bar in the non-repaired reference concrete is the only corroding bar, that is, it is the only one able to maintain the corrosion cell with the anodic region stable. The repair systems were not able to prevent the onset of corrosion in the secondary bars, even though these bars had a minimum cover thickness of 5 cm. This occurred because the original reference concrete had a high initial chloride content which initiated the rapid corrosion transfer (in about 1 year) of the electrochemical cell. For concrete contaminated with chlorides



that have penetrated from the environment, the process of transference of corrosion cells may take longer and consequently the repair system in a short period may be mistakenly considered efficient.

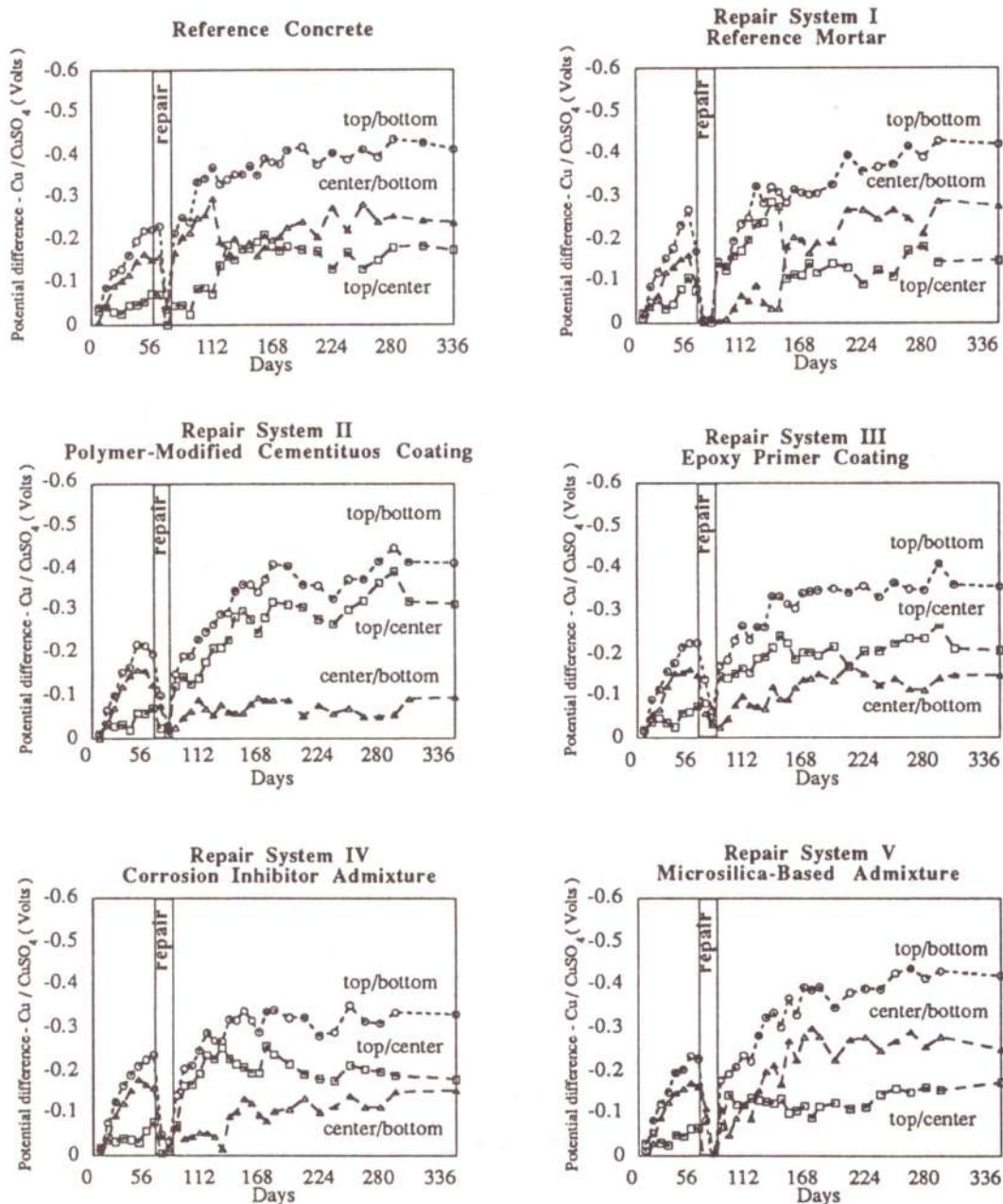
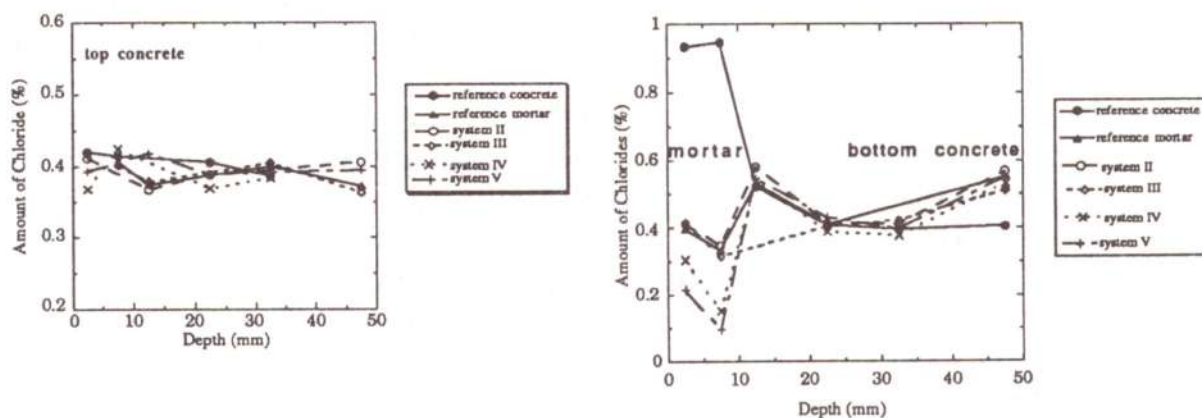


Figure 4 - Corrosion potential difference (V) between the three studied regions (top, center, and base) of the reinforced prismatic specimens with reference to the main bar

The average chlorides content in the top regions of the concrete specimens was practically constant around 0.4% by mass of cement, which is typical for a region without corrosion (Fig. 5a).

The same can not be said for the corroded regions (Fig. 5b). Mortar containing microsilica (system V) or corrosion inhibitor admixtures (system IV) had lower penetration of chlorides than the reference mortar. It was also observed a high chloride content close to the corroded bars, whereas in specimens prepared with the reference concrete there was no increase in chloride concentration near the steel bars. This fact illustrates the chloride ion migration which is driven by the electric field created as a result of the formation of electrochemical corrosion cells.



(a) non-repaired region

(b) repaired region

Figure 5 - Average mass content of chlorides as a function of cement mass at the top region of the specimens (non-repaired region).

Systems IV and V had the best performance and provided superior protection in the repaired region. These results confirm the efficiency of the corrosion inhibitor products containing calcium nitrite in delaying the corrosion processes and the ability of mortar containing microsilica to reduce the diffusivity of ions and prevent the chloride ion penetration for a long period of time.

## CONCLUSIONS

This experimental investigation was based on a limited number of repair systems: mortar, polymer modified cement paste paint applied to the steel, epoxy coating on the steel surface, corrosion inhibitor admixture added to the mortar, and microsilica based admixture added to the reference mortar. Based on the observed test results the following conclusions appear to be warranted:

a) for concrete of medium quality exposed to aggressive medium and with high levels of contamination from the environment, the



localized repairs may cause the onset of corrosion in other locations, increasing the problem instead of solving it; that is, there is a high risk of transference of the cells of electrochemical corrosion, alternating positions between anodes and cathodes. In this case, a localized repair system of the types used in these tests should not be adopted. It remains to be seen whether or not other methods of local repair are able to prevent the transference of the cells of electrochemical corrosion. Complementary measures<sup>10</sup> such as reduction of the ambient aggressiveness, superficial protection through barriers, re-alkalinization of the concrete, electrochemical removal of the contaminants, and cathodic protection (galvanic or with impressed currents) should be used;

b) corrosion inhibitors and microsilica used as admixtures in the repair mortar were able to protect and maintain the passivation of the steel bars in the repaired regions;

c) the polymer modified cement and epoxy paints used in this study, as well as the traditional mortar of cement and sand, were not able to prevent the return of corrosion in the repaired regions;

d) there is a need to develop methods for testing the quality the repair in concrete structures with corroded steel bars. Only the analyses of the protection obtained in the repaired locations are not enough, since other variables may be at play. Corrosion potential measurements help the monitoring of the phenomenon but visual observation and determination of the loss of mass still appear to be necessary. New developments, such as electrochemical impedance<sup>11</sup> and polarization resistance<sup>12</sup> may be incorporated in these analyses of performance to improve the understanding of the processes involved.

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