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STRUCTURAL SHAPE EFFECT ON REHABILITATION OF VERTICAL CONCRETE STRUCTURES BY ECE TECHNIQUE

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ABSTRACT

Electro-migration of ionic species due to cathodic polarization is used to extract chloride ions from reinforced concrete, hence, the name electrochemical chloride extraction, (ECE). The embedded reinforcing steel is made cathodic with respect to an externally placed anode blanketed within suitable electrolyte-holding fibre material. In the present study, an examination has been made of the effect of structural (design) requirements and the geometric configurations of different reinforced concrete (r.c.) column specimens. Also of practical concern was the fate of the chloride ions within the r.c. column hoop and opposite face of the anode during the ECE application. This is because the extraction application is from one face of the column structure, and secondly, the chloride ions must pass between negatively charged rebars in order to exit the structure. It is observed that circular columns containing spiral reinforcements show better ECE performance than structures with planar surfaces. In most cases, the geometrical curvatures in candidate systems will require (structurally), a more closely spaced reinforcing steel and ties. Hence, the proximity of such reinforcing steel and ties, as well as the greater total steel quantity means an efficient ECE system.

Introduction

Reinforced concrete deterioration due to chloride-induced corrosion of embedded reinforcing steel can cause abrupt structural collapse [1]. The use of deicing salts during the winter months and intentional additions of chloride-based admixtures during concrete mixing introduce substantial amounts of the aggressive species. Other sources include the use of contaminated aggregates or mixing water, and exposure to industrial brine and seawater. The chloride ions exist either in bound form with hydration products of cement such as hydrated C_3A or C_4AF phases and CSH gel, or freely dissolved in the capillary pore solution. It is in the later state that it is readily available to attack steel.

The main features of electrochemical corrosion of steel in concrete are well known. In the absence of an external electrical source in a concrete structure, the process requires two half cell

TABLE 1

Concrete Mix

Cement, OPC Type 10	432 Kg/m^3
Sand	600 Kg/m^3
Pea stones, 10mm max.	1150 Kg/m^3
Water	130 Kg/m^3
AEA	6%
Water reducer	1 ml/Kg cem.
Superplasticizer	2.8 ml/Kg cem.
Chloride ions	1.7% & 3.0 % by cem. weight

(redox) reactions. For these redox couples to satisfy a charge balance, the rates of production and consumption of electrons must be equal. In any case where more electrons are artificially (externally) supplied, thereby decreasing the incentive for the anodic reaction rate, corrosion is retarded or even stopped.

Electrochemical chloride ion extraction, (ECE), from reinforced concrete structures has become a viable means of abating corrosion damage [2–5]. The process is similar in principle to impressed current cathodic protection (CP), but involves a one-time application of a few days or weeks compared with the life time application necessary for CP systems. In both cases, the electrochemical behaviour of steel in concrete depends on cement paste pore solution around the steel. The principal aim of ECE is to reduce the chloride ion concentration to levels that will permit repassivation of the reinforcing steel in the highly alkaline cement paste. The treatment limits available Cl^- ions being able to sustain electrochemical corrosion and restores sufficient alkalinity at the steel-concrete interface.

Present research on the process focuses on design and durability implications. In this study, an examination has been made of the effect of structural requirements and geometric configurations of candidate ECE concrete structures. Also of practical concern during ECE application is the fate of chloride ions enveloped by the reinforcement cage. As the ECE application is from one face of the column structure, the question arises as to the direction the migration path of core-trapped Cl^- ions will take in view of the repulsive potentials of the cathodic steel. Also, any migrating ion must pass between negatively charged rebars in order to exit the structure. Thus, the design and efficiency of ECE systems basically depends on total applied electric charge that passes a unit area of concrete-steel interface.

Specimen Preparation

Four reinforced concrete columns 1200 mm long were cast using a ready-mix concrete as shown in Table 1. The ECE test system was comprised of two square-sectioned r.c. columns (300 mm x 300 mm) which were designated as columns #1 and #2, and two circular-sectioned r.c. columns (300 mm diameter) designated as columns #3 and #4. Both specimens of the same type were reinforced with similarly shaped cages fabricated from 15M (ASTM #5) deformed rebar. The circular-shaped r.c. columns were reinforced with six longitudinal rebars and a spiral geometric configuration of hoop steel. All the lateral reinforcement (ties) in circular-shaped columns were displaced with respect to one another due to the spiral nature. Similarly, the

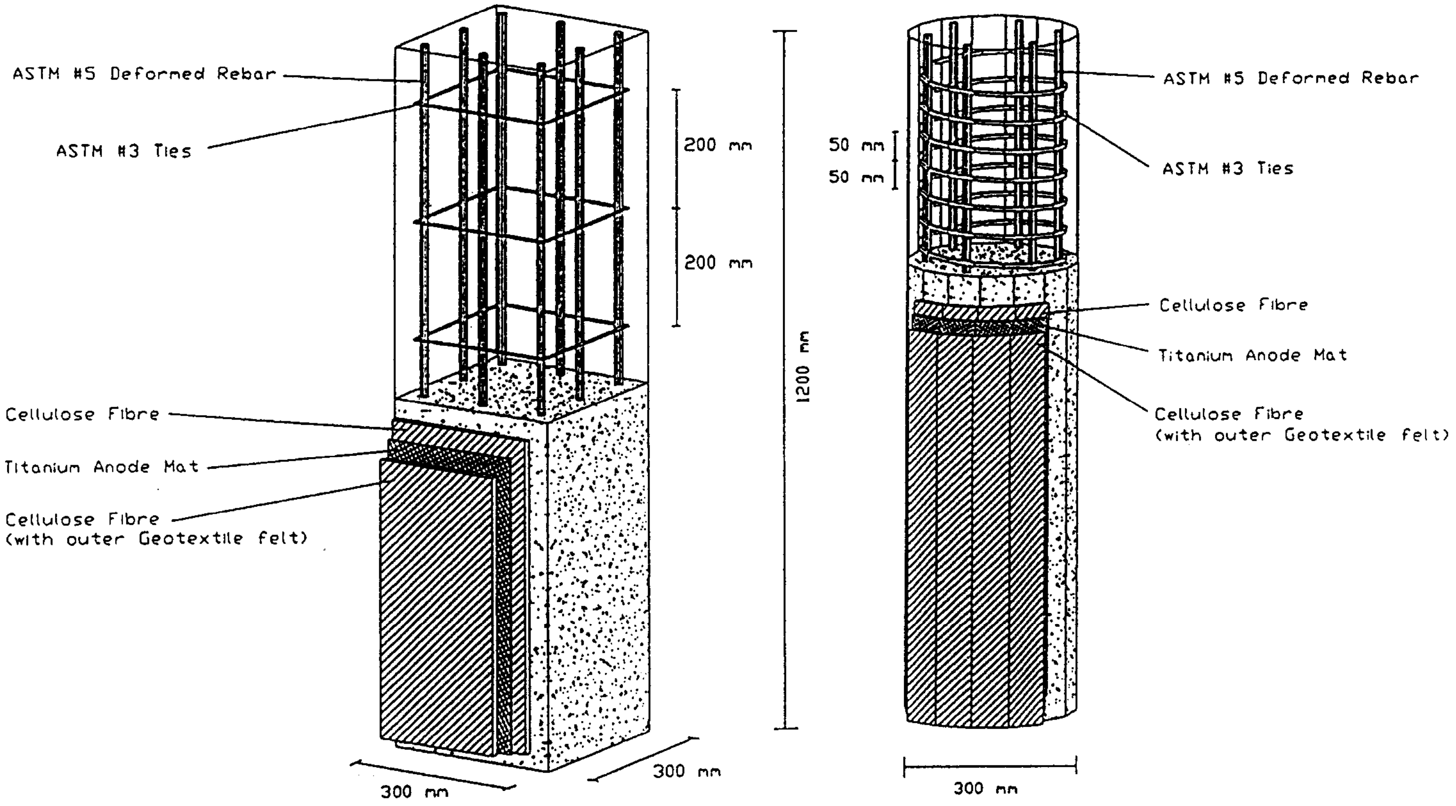

FIG. 1.
Schematic of R.C. columns-cut to show embedded rebars.

reinforcement type used in columns #3 and #4 comprised of eight longitudinal rebars and 250 mm × 250 mm square ties in which the ties were aligned over each other as done in practice. The free standing columns, schematically shown as Fig. 1, were cast in two concrete lifts of differing Cl^- ion contents. Premixed Cl^- ion (as NaCl) in the central 150 mm wide core was 1.7% (by weight of cement), while the outer concrete surround contained 3.0% (by weight of cement).

The ECE system consisted of an anode mesh placed within electrolyte-holding cellulose fibre blankets constructed on one quarter surface area of each specimen. The system electrolyte, saturated calcium hydroxide, was pumped from the base of the specimens to an overhead tank and allowed to flow through the anode system by gravity. The anode was an inert titanium wire mesh (ELGARD EC300). The anode was electrically coupled to the positive terminal of a rectified (and filtered) DC power source, and the circuit completed by connecting to the reinforcing steel with wires incorporating 1.5Ω shunts for periodic monitoring of applied current. The ECE treatment was continuously operated without interruption for eight weeks. The concrete age at the start of ECE was five months. The reinforcing steel depolarization subsequent to the ECE process was monitored for two weeks and thereafter the ECE systems were re-applied to one of each column type for a period of two weeks. Concrete cores were drilled, sliced and pulverized before and after each segment of treatment for ionic analysis. The Cl^- ion profiles were determined by potentiometric titration with silver nitrate using standard protocol outlined in AASHTO T-260. The free chlorides were digested in hot water while conc. nitric acid was used to determine the total chlorides. Atomic absorption spectrophotometry was used to determine the sodium (Na^+) and potassium (K^+) ions.

Mechanism of ECE

ECE application to the r.c. columns was accomplished by cathodically polarizing the rebars using a direct current density of 1 A/m^2 (0.1 A/ft^2) of concrete surface covered by the anode system. The governing transport mechanism for electrolyte penetration and/or ionic migration out of concrete is electro-migration of charged species imposed by the electric field gradient. Other physical processes, which in most cases are neglected, include bulk electrolyte flow by electro-osmosis and direct absorption, and simple ionic diffusion induced by prevailing concentration gradients. Electrochemical processes that occur at the rebar-concrete system during the cathodic polarization generate hydroxyl (OH^-) ions and protons (H^+) through water hydrolysis as shown in Equations 1 and 2 respectively;

Cathode reaction:

$$4H_2O + 4e^- \rightarrow 2H_2 + 4OH^- \tag{1}$$

Anode reaction:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \tag{2}$$

In addition to the oxygen reduction reaction (Equation 1) at the steel-concrete interface, it is also possible to generate hydrogen gas according to Equation 3. This is because of the level of cathodic polarization in which the steel potential is forced below the hydrogen line (i.e., line ‘a’) on the Pourbaix diagram [6]. Pourbaix diagrams describe the effect of electrochemical potential and pH on the behaviour of metals in an aqueous media. Hydrogen gas has been detected at steel potentials of about -1.1V CSE in cathodic protection of reinforced concrete [7].

$$\begin{gathered} 2H^+ + 2e^- \rightarrow 2H \\ 2H \rightarrow H_2 \end{gathered} \tag{3}$$

However, at the later stages when there are fewer chloride ions to carry the electrical charge, the cell voltage tend to rise and there is an increase in the electrical resistivity of the concrete system. As a result, there is the possibility of oxidation of extracted Cl^- ions according to Equation 4, which may lead to chlorine evolution at the anode-electrolyte part of the system;

$$4Cl^- \rightarrow 2Cl_2 + 4e^- \tag{4}$$

The ionic migration due to ECE involves transport of Cl^- ions away from the rebars and out of the concrete towards the external anode. Cations (predominantly Na^+, K^+ and Ca^{++} ions) migrate towards the vicinity of rebars under the influence of the applied electrical field. In addition to the accumulations of the cations, hydroxyl ions which are produced at the rebars, contributes to their repassivation. The application of ECE can remove both free Cl^- ions, and cause the decomposition of the chloroaluminate compounds, the later process releasing bound Cl^- ions for further removal [8].

Results

Electro-migration induced a significant reduction in chloride ion concentration of the r.c. columns from the cast-in levels. This was achieved in greater proportions in concrete cover regions of all specimens, and in diminishing proportions in the interior of the columns. The reductions in chloride concentration of the concrete cores obtained from the lower sections of the r.c. columns were more pronounced than that obtained from the upper sections. This is probably due to differential permeation of the ECE electrolyte into the concrete as well as inhomogeneous wetness.

In r.c. columns #1 and #2, which were circular-sectioned, the premixed chloride concentration of between 5000–6000 ppm (by concrete weight) was reduced to about 1800–3000 ppm (by concrete weight) by the first ECE application. The chloride ion profiles are shown in Figs. 2 and 3, respectively. Also, an average reduction in chloride content obtained at the sampled points of this specimen type was about 2200 ppm (by concrete weight). From Figs. 4 and 5, it is observed that the chloride ion concentration in square-sectioned r.c. columns #3 and #4, which was initially at 5000–6000 ppm (concrete weight), was reduced to about 3000–4000 ppm (by concrete weight) by the first ECE application. These reductions were mainly observed in the high chloride concentration zones of the cover concrete in both r.c. columns. Within the concrete core of both specimen types, the reduction in chloride ion concentration averaged about 400 ppm (by concrete weight) due to the low level of premixed chlorides, and probably as a result of the repulsive nature of the applied potential of the hoop steel.

There was some initial fluctuation of applied current density in all ECE systems though this became, more or less, steady as the concrete became saturated with the treatment electrolyte. The applied current was monitored by measuring the voltage drop across a resistor placed on the circuit wire between the steel and the negative terminal of the rectifier. It is believed that

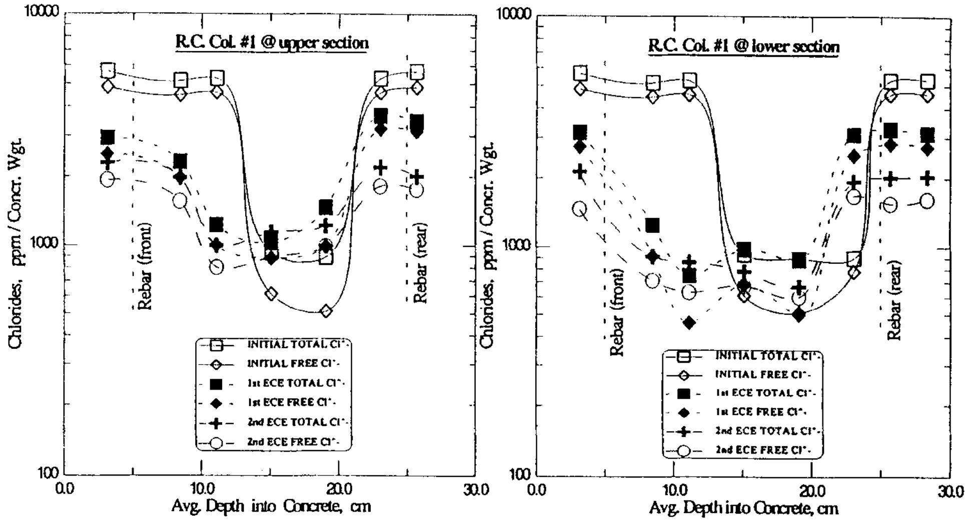

FIG. 2.
Chloride profiles in R.C. Col. #1 (circular shape).

the subsequent variation of applied current with extraction time is most likely due to the slower process of ionic conduction in the pore structure in comparison with electronic conduction by the steel rebars [9]. Despite the scatter of the ionic profiles, the repulsive action of negatively charged rebars during the ECE process can also cause trapping of Cl^- ions in the core concrete within the steel cage as shown in the central part of Figs. 2–5. The trapped Cl^- ions which could not be initially extracted were expected to redistribute upon removal of the applied electric field and subsequent depolarization of the rebars, the result of which might be a re-initiation of

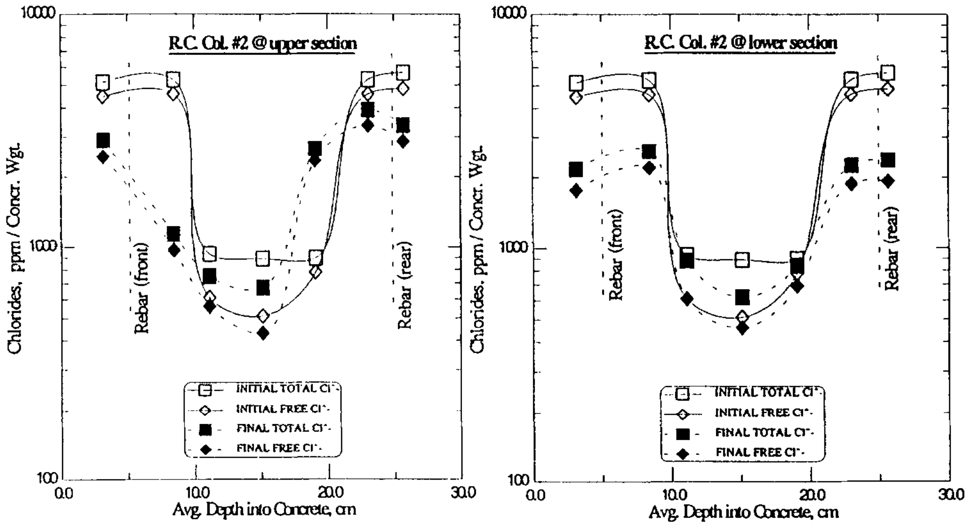

FIG. 3.
Chloride profiles in R.C. Col. #2 (circular shape).

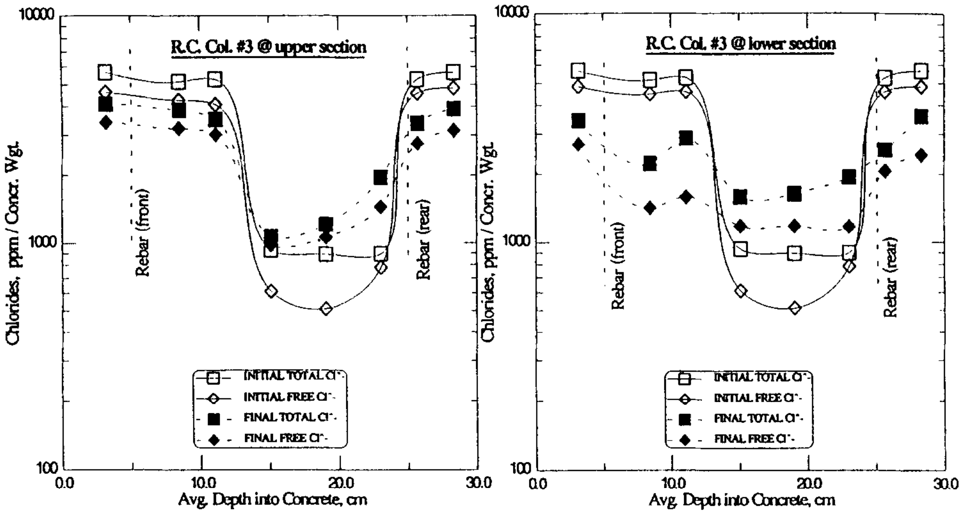

FIG. 4.
Chloride profiles in R.C. Col. #3 (square shape).

corrosion! However, a second application of the ECE process to r.c. columns #1 (circular-sectioned) and #4 (square-sectioned) enabled a more efficient removal of chlorides in the core concrete as shown in Figs. 2 and 5 respectively. An average chloride ion reduction of about 600 ppm (by concrete weight) was obtained in column #1 compared with about 200 ppm (by concrete weight) in column #4. Though the Cl^- ion profiles in the two specimens changed somewhat upon the re-application of the ECE systems, more changes were observed in the lower sections of the columns than at the top sections as observed during the first application.

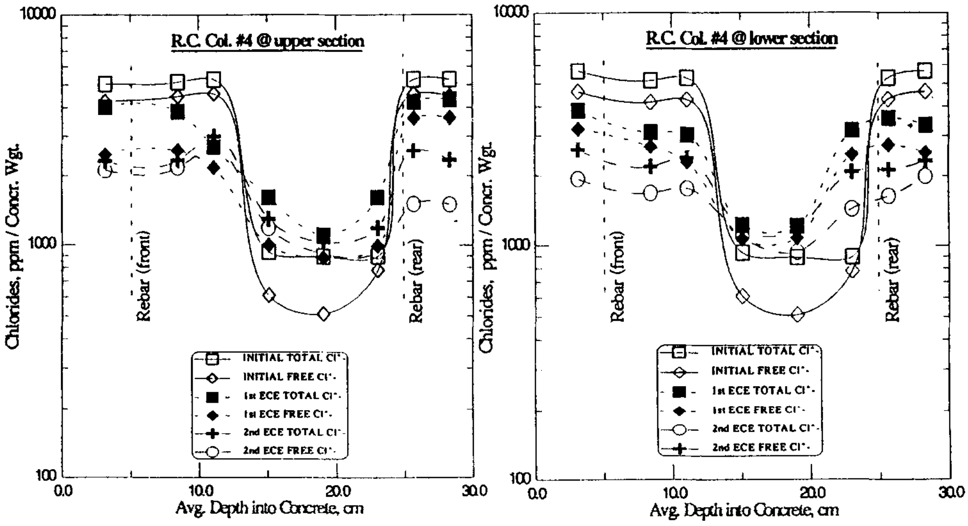

FIG. 5.
Chloride profiles in R.C. Col. #4 (square shape).

TABLE 2: Influence of ECE on Steel Corrosion Potential (vs Graphite)

Concrete Age	Col. #1	Col. #2	Col. #3	Col. #4
days	mV	mV	mV	mV
49	-241	-288	-280	-288
104	-268	-271	-243	-240
152*	-303	-340	-248	-232
213**	-337	-677	-468	-677
228†	-	-388	-188	-
243††	-465	-281	-180	-370
303	-187	-260	-147	-187
412	-74	-245	-140	-101
435	-75	-201	-123	-97
503	-73	-166	-105	-87

*Before 1st ECE, **End 1st ECE; †Start 2nd ECE, ††End 2nd ECE
** & †† Measured 24 hrs after ECE

In the r.c. columns subjected to a second ECE application, the shift in steel potential measured initially before any chloride removal and 24 hours after the second ECE was up to 250 mV, compared with about 100 mV observed in specimens in which single ECE treatment was adopted as shown in Table 2. The disproportionate chloride removal, non-uniform hydroxyl ion production and concrete inhomogeneities may have contributed to the different corrosion potentials.

The rehabilitation of r.c. concrete structures requires substantial electro-migration of the alkali metals to the rebar region during ECE treatment as a result of cathodic action. Ionic profiling indicate significant accumulations of alkali ions of sodium (Na^+) and potassium (K^+) in the vicinity of the reinforcing steel [10]. It is expected that this will assure repassivation of reinforcing steel in ECE systems in which an efficient removal of chlorides was obtained. Again, it was observed that the circular-sectioned specimens had higher cation accumulations in the concrete region near the rebars. But such cation accumulations can also cause harmful chemical changes, and paste discolourations have been observed elsewhere [5,11]. It is also possible that the presence of dissolved ions at these locations, the pH changes, and the evolution of H_2 gas as a result of the electrodic processes can also initiate the observed cement paste degradation.

The rapid loss of alkalinity in the ECE system electrolyte necessitated frequent additions of $Ca(OH)_2$. Ordinarily, such electrolyte degradation is related to the Cl^- ion removal rate which expectedly is higher during the early stages. In the early stage, when Cl^- ion contamination is high more Cl^- ions are extracted than OH^- ions. Subsequently, due to the fewer Cl^- ions available to carry the electrical charge during the later stages more OH^- ions are then extracted resulting in reduced pH. The rapid depletion of OH^- ions generated by the hydrolysis of water and the possibility of electrolyte carbonation may mean frequent $Ca(OH)_2$ additions. However, the use and frequency of regeneration of saturated calcium hydroxide in this study may make the electrolyte unattractive in practice.

Discussion

A fully curved concrete structure, incorporating a spiral reinforcing steel configuration, expectedly can cause some interference in ionic migration paths. In most cases, structural design requires hoop steel of similar geometry as the concrete structure, hence the displacement of spiral steel as it climbs the column height may mean irregular ionic migration paths. Since the ECE application was from one face of the structures, the chloride ions at the rear side (with respect to the anode location) was expected to be trapped at such depths. But it is observed that the geometrical curvature effect did actually sustain frontal migration of chlorides towards the anode system. This is depicted in the chloride profiles in both square-sectioned and circular-sectioned r.c. column types shown as Figs. 2 and 3 and 4 and 5 respectively. The fact that Cl^- ions within the concrete core of the rebar cage had to pass between negatively charged rebars in order to reach the anode, had differing implications in the systems under test. In the rectangular-sectioned structures, this resulted in an ionic build-up rather than reduction in the core of the column, as shown in the central part of Figs. 4 and 5. In the test systems, the Cl^- ion extraction at the back of the specimens (i.e., opposite face of anode system) was not as pronounced as within the vicinity of the rebars and may have contributed to the ionic accumulations. From numerical studies which were based on finite difference approach, it has been suggested that such "saddle points" probably result from the net negative charges on the reinforcing steel [9].

Despite the fact that the Cl^- ions within the concrete core of the reinforcing steel cages had to pass between the negatively charged rebars in order to reach the anode, there was a significant reduction in Cl^- ion profiles in the frontal half of the specimen cross-sections. However, the Cl^- ions behind the opposite face of the anode system were effectively repelled from the vicinity of the rebars thereby causing an "increase" in Cl^- ion levels of concrete in the other half of the specimens. This is evident in Figs. 2 and 3 representing the chloride profiles for the circular-sectioned columns (#1 and #2).

In uncarbonated concrete such as the tested specimens, aluminate compounds of C_3A or C_4AF, combine with some Cl^- ions to form complex compounds. Since such Cl^- ions are bound by the nature of their reaction, the free Cl^- ions will only be available for removal. In most cases, the free Cl^- ions will exist in equilibrium with the chloroaluminate compounds:

$$CaCl_2 + 3CaO.Al_2O_3 + 10H_2O \equiv 3CaO.CaCl_2.Al_2O_3.10H_2O \qquad (5)$$

The depletion of free Cl^- ions during ECE can cause a breakdown of these compounds in order to replenish the free Cl^- ion level [8]. The time requirement for release of bound chlorides is likely to be slower than that of extraction. The time-lag may contribute to disproportionate chloride removal with treatment time as observed elsewhere [12], hence the additional need in this study to incorporate an extraction rest time, and subsequent re-application of the ECE system. In addition, such an intermittently applied electric power will offer a cool-off period for rebar depolarization in systems in which the polarization level is considered high enough to cause possible damage.

In the r.c. columns investigated, ECE system performance is found to be dependent on the configuration of the reinforcing steel cage and total quantity of steel available for cathodic polarization. Both factors result from structural engineering requirements. As a result, concrete structures with circular shapes usually contain more quantity of steel than square or rectangular shapes at the same load carrying capacity, which also applies to the specimens used in this study. Hence circular-sectioned concrete columns with more closely spaced steel per unit area will offer more polarization current density. It then follows that the degree of chloride ion contamination of a structure in relation to the total charge that passes a unit area of concrete-steel interface influences the system performance. In the present experimental system, with a constant applied current density with respect to the concrete surface, the total applied electric charge passing a unit area of concrete-steel interface was dependent on the total quantity of reinforcing steel in the structure, period of power application, and configuration and placement depths of the reinforcing steel cage.

The observed higher reduction in Cl^- ion contents in the geometrically curved specimens compared with specimens with square shapes may have structural implications. Though there is need for further work to better understand the implications for an efficient ECE performance and thus, corrosion mitigation. However, the use of an alternative anode system that wraps around the candidate structure is a good option. In situations where this is not feasible, a good remedial measure may require either a supplemental anode system on the opposite side of the structure or an intermittent ECE application to assure a more efficient removal of chlorides. In any case, the observed trend in ionic migration in the opposite side of the anode system is obviously advantageous to rebar corrosion mitigation.

Conclusions

1. It is possible to reduce the chloride ion content from the core concrete section enclosed by the reinforcing steel cage, and outside the steel hoops even when ECE is operated from only one face of a candidate structure.
2. The structural (design) requirements and geometry of a candidate structure will influence the ECE system performance, and consequent residual chloride profiles. Geometrically curved structures reinforced with longitudinal steel and spiral ties shows promise of a better Cl^- ion extraction, than in structures with planar surfaces incorporating rectangular hoops.
3. Chloride ion extraction is found to be dependent on both configuration of the reinforcing steel cage (which results from the structural shape) and total quantity of steel available for cathodic polarization. The structural implication is that a supplemental ECE application may be necessary in systems with planar surfaces than those with geometrically curved surfaces.
4. In general, there are significant reductions in all specimens of both total (acid-soluble) and free (water-soluble) chlorides.

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