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Effects of stirrups on electrochemical chloride removal efficiency

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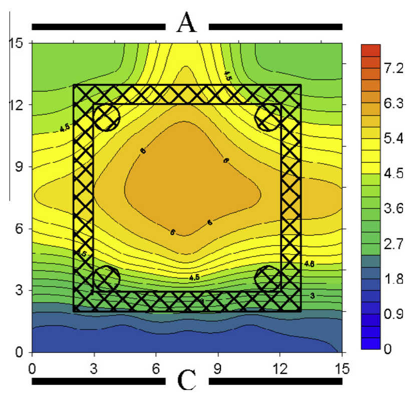
HIGHLIGHTS

- The existence of steel reinforce cage hinders the removal for chloride ions enclosed by it.
- The electrochemical signals showed that after ECR the corrosion tended to be retarded.
- The ECR may induce leaching of calcium ions inside concrete.

GRAPHICAL ABSTRACT

Chloride ions inside the cage did not move by the ECR process.



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ABSTRACT

In this paper, how the stirrups influence the efficiency of electrochemical chloride removal (ECR) is studied. The chloride removal efficiency was investigated by examining the chloride contents in concrete. In addition, the electrochemical signals for corrosion status for the rebars were recorded and analyzed. While the stirrups existed and formed a connected electric path with rebars, due to the fact that the electric potential for the steel rebar cage remains the same everywhere on the rebar cage the chloride enclosed by the steel rebar cage was difficult to be removed no matter how the electrodes were arranged. Although the chloride ions enclosed by the rebar cage were not easy to be removed, the electrochemical signals showed that after ECR the corrosion tended to be retarded.

1. Introduction

It is well known that the existence of chloride ions in reinforced concrete structure or prestressed concrete structure influence the durability of the members. For example, concrete pavements constructed by concrete may suffer from deicing salt and serious corrosion happens while the chloride ions content is too high. The chloride ions will destroy the passive film which is formed in a very high alkaline pore solution and results in corrosion. Therefore, one needs to consider the effects of chloride ions before construction process and make a reasonable mix design to ensure the durability of the concrete structures. An overall review article about the durability of steel reinforced concrete structures can be found in [1].

Once the chloride ions content is found to be too high, one may remove unsound concrete and recast repair materials or one can consider the electrochemical chloride removal process. Assessments and guidelines for treatment were issued following the Strategic Highways Research Program (SHRP in the USA)—such as

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SHRP-S-347 and SHRP-C-620. These can be downloaded from the web. In addition, the processes were the subject of several patents which formed the basis of the "Norcure" processes that have been fairly widely known and used in USA, Europe and Japan.

The idea of ECR involves mounting an anode surrounded by a liquid electrolyte (usually NaOH or Na_3BO_3) on the surface of concrete and driving direct current into the embedded reinforcement, which acts as a cathode. (The usual electrolyte is calcium hydroxide provided as a saturated solution by mixing cellulose pulp with solid hydrated lime. This captures some fugitive chlorine and also prevents acid etching of the concrete surface). The current pushes chloride ions away from the reinforcement and extracts them towards the anode. Once reaching the concrete surface, the ions eventually pass into the anolyte and are thereby removed from concrete.

There exist numerous papers about ECR, the followings are some of them.

Garcés et al. [2] studied the effects of bar arrangements on the ECR efficiency. Five different types of bar arrangements were considered, corresponding to typical structural members such as columns (with single and double bar reinforcing), slabs, beams and footings. They concluded that the ECR efficiency was influenced by the type of bar arrangement and a uniform layer set-up favors chloride extraction.

Hassanein et al. [3] reported that factors that affected the short-term chloride removal efficiency included the resistivity of concrete, charge passed, treatment duration, initial chloride content, concrete cover, and chloride diffusion coefficient. Among these factors, the resistivity of concrete, charge passed and chloride diffusion coefficient were influenced by the water/cement (or water/binder) ratio.

Yeih et al. [4] studied the influence of the polarization parameter (defined as the desalination current density times the duration of ECR) on the ECR efficiency. They reported that as this parameter increased the chloride ion content inside concrete decreased.

Elsener and Angst [5] published a paper to discuss the mechanism of ECR. They have found that due to the removal of free chloride during the treatment, bound chloride is dissolved in order to re-establish the equilibrium between bound and free chlorides. The rate of release of bound chloride is slow compared to the rate of chloride removal and thus the ECR process quickly becomes inefficient. Current off periods allow the system to re-establish the equilibrium between bound and free chlorides. Subsequently, the process is efficient again.

Wang, Li and Page [6] used the mathematical model and numerical method to study the ECR for a 2-D member. Toumi, François and Alvarado [7] used numerical method to simulate ECR and compared results with experimental works.

Herrera et al. [8] studied the efficiency of ECR for various C_3A content, they concluded that ECE efficiency was slightly affected by C_3A because only a part of the bound chloride ions was released.

Orellan et al. [9] reported that after treatment, new cementitious phases containing rich concentrations of sodium, aluminum and potassium were formed. Moreover, alkali–silica gel was observed. They have concluded that the ECE accumulates locally high amounts of alkali ions that stimulate the alkali–silica reaction even though the concrete contained nominally inert siliceous aggregates.

Siegwart et al. [10] reported that the ECR process would result in hydrogen embrittlement thus was not suitable for prestressed concrete. They concluded that the risk of hydrogen induced brittle fracture due to electrochemical chloride extraction cannot be altered with modification of the treatment parameters, such as current density or treatment duration.

Fajardo et al. [11] reported that after ECR, about 60% to 50% of the initial chloride was removed from the concrete on average. Around 1% chloride by mass of cement remained around the steel after treatment. They also claimed that although both the chloride content and the dissolution of the steel were reduced, the repassivation of steel rebar cannot be guaranteed.

Pérez et al. [12] studied the ECR efficiency by using the conducting cement as the anode. They found that the thickness of the conductive cement paste anode has a great influence on the capacity of the anode to retain an important part of the extracted chlorides after finishing the electrochemical treatments.

Siegwart et al. [13] have reported that the pore size and pore size distribution of concrete are altered due to ECR and small pores hinder the migration of ions, which may partially be responsible for changes in concrete resistance.

Ihekwaba et al. [14] also reported that the ECR current reduced the concrete compressive strength, especially for the concrete near the cathode. By investigating the rehabilitation of several vertical structures, Ihekwaba et al. [15] concluded that circular columns containing spiral reinforcements showed better ECR performance than structures with planar surfaces. They [16] also reported that a pullout bond degradation of steel rebars in ECR concrete with a maximum decrease of 44% bond degradation was found.

Cañón et al. [17] found the sprayed conductive graphite powder–cement paste as anode not only provides electrochemical chloride removal with similar efficiency, but also is able to retain moisture even without the use of a continuous dampening system.

Miranda et al. [18] reported that if ECR is applied preventively it is an efficient procedure for delaying the start of corrosion. However, if applied too late it does not assure the repassivation of corroded RCS and is therefore useless.

Arya et al. [19] studied the factors that influence ECR and they concluded that chloride removal increased with increasing applied potential, number of reinforcing bars at a particular depth and initial chloride content of the concrete. A greater percentage of chloride was removed from prisms where the thickness of the chloride bearing layer of concrete was less than the depth of cover to the reinforcement. Where the thickness of the chloride bearing layer exceeded the cover to the reinforcement, the use of an external cathode significantly increased the total amount of chloride removed.

In this study, the effect of stirrups on ECR is examined. When stirrups and rebars together form a reinforcement cage, theoretically speaking they form a connected electric current path and the electric potential should be the same. In such a case, whether

Table 1
Concrete mix design.

w/c	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	NaCl (kg/m^3)
0.5	196	393	662	1046	11.79

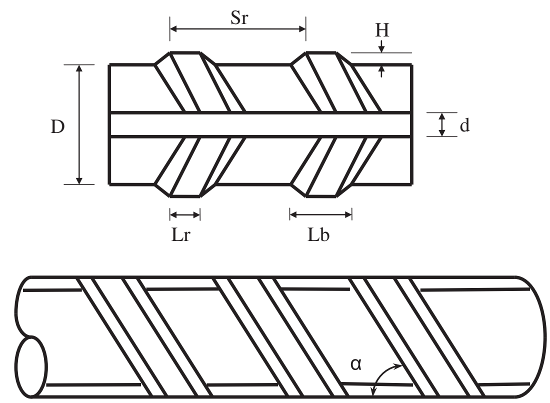

Fig. 1. Geometric diagrams of rebar.