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PULL-OUT AND BOND DEGRADATION OF STEEL REBARS IN ECE CONCRETE

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ABSTRACT

It is demonstrated in this study that application of electrochemical chloride extraction (ECE) to reinforced concrete alters the pull-out strength and bond between the embedded high strength steel (HSS) and surrounding concrete. Concrete cubes were cast using two chloride (Cl^-) ion concentrations of 1.7% and 3.0% by weight of cement respectively, and reinforced axially with a central ASTM #6 plain steel bar. Two cathodic (d.c.) current densities, 1.0 A/m^2 and 3.0 A/m^2 of concrete surface, were used for the ECE studies, with 0.1M sodium borate electrolyte solution and inert titanium anode mesh. Axial pull-out tests as per ASTM Standard Test Method C234-91a, were carried out within 24 hours of terminating treatment to investigate the differences in bond stress and bar slip behaviour. ECE treated specimens showed significant reductions in pull-out strength, with the degradation in bond being dependent on the applied cathodic current density and initial chloride contamination. At an impressed current density of 3.0 A/m^2, the 1.7% Cl^- ions specimens showed about 58% loss in bond strength compared with about 44% for specimens premixed with 3.0% Cl^- ion. The bond strength reduction at an impressed current density of 1.0 A/m^2 was about half the reduction at current density of 3.0 A/m^2. The loss in bond strength were based on (untreated) control specimens of each type. The alkali ion accumulations around the steel rebars were observed to follow similar trend as bond degradation. It is predicted the softening effect of the alkali (sodium and potassium) ions on the cement silicate hydrates around the steel-concrete interface will have severe effect on concrete structures reinforced with HSS irrespective of their stress state. Also, concrete structures containing steel rebars with substantial corrosion product coverage are likely to experience pronounced cathodic disbondment during ECE application and within a few days of terminating the treatment.

Introduction

Over the last two decades, the use of electrical methods of mitigating corrosion of reinforcing steel embedded in concrete due to the ingress of chlorides has been the subject of many research and field testing programs [1-5]. The application of impressed current cathodic protection (CP) to high-strength reinforcing steel embedded in concrete, which is the principal electrical method in use, can provoke degradation of the interface between steel and concrete [6]. The problem is perceived to be most critical in prestressed concrete containing bonded (pretentioned) cables and in systems which are cathodically over-protected. In addition, the huge operational costs of maintaining CP systems have stimulated the recent research interest in electrochemical chloride ion extraction (ECE) as an alternative and cost-effective rehabilitation method for steel reinforced concrete structures undergoing deterioration due to chloride-induced corrosion.

The electrochemical principles of ECE and impressed current CP applications to steel reinforced concrete are similar, although the level of applied cathodic polarization current density employed in ECE studies are many times higher than in CP systems. The relatively high ECE current density required in practice for ionic electromigration is applied for a few weeks or days depending on the degree of chloride contamination and quantity of steel rebars available for polarization, whilst CP requires a fraction of the same current density for the entire service life of the structure. It is suspected that ECE application to prestressed and conventional reinforced concrete structures can exacerbate electrochemical reactions (or electrode processes) that cause steel-concrete bond loss such as observed in conventional CP systems hence the need for the present investigation. Due to such perceptions there has been limited field application of ECE as an alternative rehabilitation method to cathodic protection (CP) for concrete structures suffering from chloride induced reinforcement corrosion. Although the merits and features of ECE application to steel reinforced concrete structures have been extensively demonstrated in previous studies [1-5], its influence on the bond of the reinforcing steel to concrete is mainly inferred from knowledge of conventional impressed current cathodic protection systems.

Electromigration of charged ions due to the applied cathodic polarization current density, as well as direct absorption and electro-osmotic permeation of the electrolyte are the principal transport mechanisms that support electrochemical extraction of chlorides in concrete structures. Ionic electromigration involves transport of both anions and cations due to the repulsive electrical potential of the embedded rebars and external anode respectively. Anions such as chlorides (Cl^-), hydroxyls (OH^-), carbonates (CO_3^{2-}), and sulphates (SO_4^{2-}) etc, are preferentially repelled from the vicinity of the rebars due to similar electrical charge polarity and thus, migrate away from the cathode region in the direction of the anode. Similarly, cations such as calcium (Ca^{2+}), potassium (K^+), and sodium (Na^+) ions migrate to the cathodic steel region in relative proportion to their respective transport numbers. Transport (or transference) number is defined as the proportion of total (applied) polarizing current carried by a specific type of ion during electro-migration, and is influenced by the resistive characteristics of the media.

Research Significance

Many aspects of ECE application such as the subsequent concrete durability and structural impact are not well understood. In majority of the cases, predictions of the structural implications of ECE on steel-concrete interface are made based on knowledge of conventional impressed current cathodic protection. It is the goal of this investigation to link a candidate concrete's macrostructural and mechanical features to the ECE process for various degrees of concrete contamination. The pull-out and bond degradation of cathodic regions of chloride contaminated concrete due to the ECE process is determined at different operating regimes.

TABLE 1

Concrete Mix

OPC Type 10 Cement	370 kg/m^3
Sand	740 kg/m^3
Pea stones, 10mm max	934 kg/m^3
Water	185 kg/m^3
AEA	6 %
Chloride ions	1.7% & 3.0% by cem. wgt.

Prediction of the electromigration and alkali ion softening effect on the cement paste and other concrete properties is shown. Bond loss values are used as an index of ECE impact on a candidate concrete system in order to insure application reliability. It is intended this approach will ensure a better understanding of the process, enable suitable formulation of application guidelines for an efficient ECE performance and structural concrete durability.

Method

A total of six series of four tests each were carried out with different operating parameters and with specimens of different concrete contamination. The traditional concentric (axial) pull-out tests as per the requirements of ASTM Standard Test Method C234-91a, were used in the study. All concrete pull-out specimens were 150 mm cubes reinforced axially with only one central ASTM #6 plain rebar using the concrete mix shown in Table 1. The steel reinforcing bars used has a minimum ultimate tensile strength of 689 MPa (100 Ksi) with a nominal chemical content as shown in Table 2. Plain (smooth) steel rebars were used to stimulate uniform bond distribution and to achieve pure slip bond failure corresponding to upper limit bond conditions. The slip bond failure is attained when the rebar just pulls out and leaves a polished surrounding concrete without further damage. The design minimizes shear contributions of any surface deformations causing concrete splitting as would occur using deformed bars, in addition to failure due to yielding of the reinforcing steel. Each steel rod was mechanically polished and degreased with acetone before embedment in concrete, and a 10 mm length at each end of the embedded part was epoxy coated to give an effective (exposed) surface area of 9430 mm^2 in the concrete cubes.

Two premixed Cl- ion contents of 1.7% and 3.0% by weight of cement (from NaCl) were used in the mix water and the resulting concrete mixes are designated as concrete batches #1 and #2 respectively. Three sets of four concrete cubes were cast from each of the two concrete batches. In addition, six 100 mm x 200 mm concrete cylinders from each batch were prepared

TABLE 2

Chemical Analysis of Steel (weight %)

Carbon	0.4/0.48	Sulphur	0.24/0.33
Manganese	1.35/1.65	Silicon	0.15/0.3
Phosphorous	0.04 max.	Copper	0.15/0.25

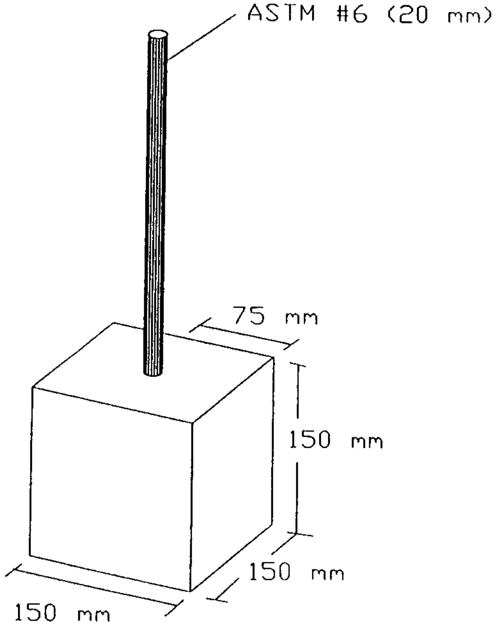

FIG. 1.
Typical ECE concrete pull-out specimen.

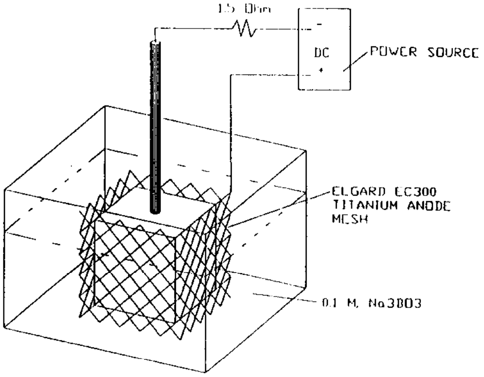

FIG 2.
Arrangement of ECE test set-up for extraction of chlorides.

for 28th day concrete compressive strength testing as per ASTM Standard Test Method C39-86, just before ECE application.

The anode system comprised of proprietary ELGARD EC300 anodized titanium wire mesh fabricated into 200 mm hollow boxes and used to enclose the concrete specimens in a tank of 0.1M sodium borate (Na_3BO_3) electrolyte solution. Schematic diagrams of the pull-out specimen and the ECE application are shown in Figures 1 and 2, respectively. The titanium anode mat was electrically coupled to the positive terminal of a rectified (and filtered) DC power source, and the circuit completed by connecting the negative terminal to the rebar with wires incorporating 1.5Ω shunts for periodic monitoring of applied current. Two sets of each concrete batch consisting of four concrete specimens with similar Cl- ion content were electrochemically treated by cathodic polarization using two direct current densities of 1.0 A/m^2 and 3.0 A/m^2 of concrete surface covered by the anode for eight weeks. These applied current densities convert to 9.5 A/m^2 and 28.6 A/m^2 of the exposed steel surface area in contact with concrete, respectively. The remaining set of specimens of each concrete batch served as control specimens, and were initially stored in plastic bags but soaked in the borate electrolyte solution for 24 hours prior to pull-out testing.

At the end of ECE treatment, wet capping compound was carefully pasted and levelled on the end of the specimens to be loaded and allowed to set overnight. The pull-out tests were carried out within 24 hours of terminating power. In accordance with ASTM C234-91a, a

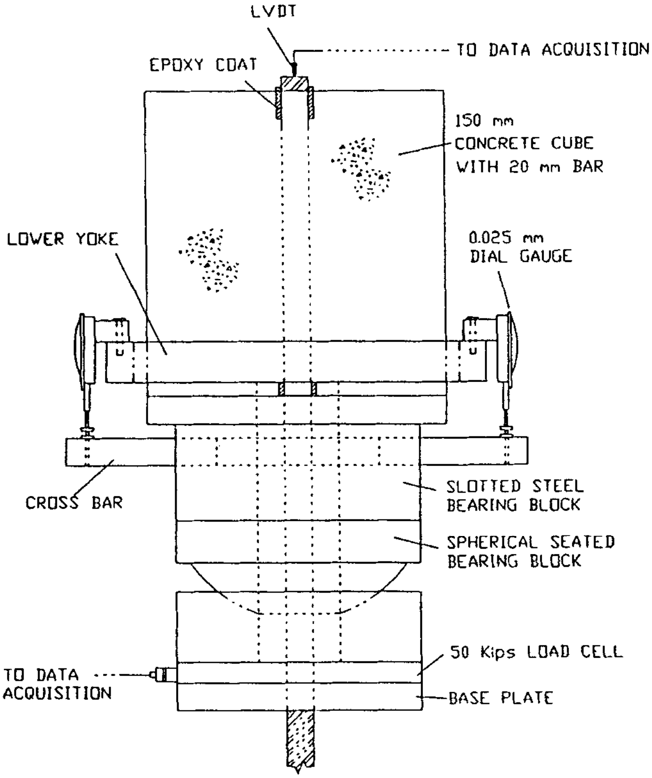

FIG. 3.
Pull-out set-up using modified ASTM Standard Test Method C234-91a.

spherically-seated bearing block with centre hole was mounted on a "StrainSert" flat load cell rated at 222.5 KN (50,000 lb) with the projecting steel rebar gripped in tension by the jaws of the 890 KN (200 Kip) Riehle universal testing machine. Two 0.0254 mm (0.001 in) dial gauges were attached by a collar around the concrete and then to a horizontal bar which was rigidly fixed to the steel rebar being pulled at the loaded end zone at a distance of 25.5 mm from the bearing surface. An average of the dial gauge readings was used as the slippage of the loaded end of the rebar after adjusting for the elastic deformation of the rebar in the distance between the concrete bearing surface and point on the pulled rebar where the dial gauge horizontal support bar was attached. A linear variable displacement transducer (LVDT) was placed at the free end to directly measure the free-end slip as the rebar was loaded in tension. Both the free-end slip and tensile loading as monitored by the LVDT and flat load cell respectively, was automatically logged by a computer controlled data-acquisition system. Figure 3 show the arrangement of a typical pull-out setup. For each chloride content, four test specimens as used at each impressed cathodic current density and four control specimens were tested. The pull-out loads were determined, and from these the bond stresses were calculated based on the embedded steel surface area, and reported as average values.

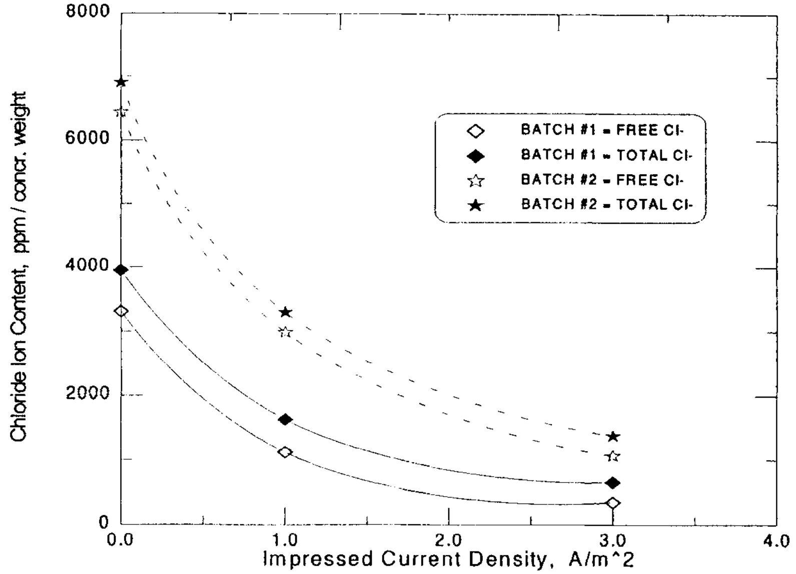

FIG. 4.
Chloride ion concentration near rebars.

After the pull-out tests, all the specimens were loaded in tension along their longitudinal axis to allow physical inspection of the concrete-steel interface. Also, concrete powder samples for ionic analysis were obtained around the perimeter of the embedded steel using a masonry drill. Chloride ion determination was carried out after initially preparing the concrete powder samples using the procedure outlined in AASHTO T-260. An automated titration system was used involving a microprocessor ion analyser which was coupled with a solid-state chloride ion activity double-junction reference electrode and a pH electrode. Chemical analysis of sodium (Na^+) and potassium (K^+) ions were carried out after digesting the concrete powder samples in nitric acid (conc.), followed with boiling and cooling overnight, and the filtrate analysed by atomic absorption spectrophotometry using protocol outlined by Perkin Elmer [7].

Results and Discussion

During electrochemical chloride extraction from steel reinforced concrete, cathodic action is characterized by the generation of hydroxyl ions, and the migration of alkali ions (mainly K^+ and Na^+ ions), released from cement hydrates as well as from the pore solution and the electrolyte, to the rebar region. The concentration of these alkali ions depend on factors such as the cement type, initial chloride-bearing compound and its associated cation, as well as the extraction electrolyte. Application of the polarizing electric field gradient necessary for electro-migration ensures ionic redistribution mainly because concrete is an ionic conductor and applied current flows as a result of the movement of dissolved ions in the cement paste pore solution. The process results in the electrochemical formation of alkali hydroxides as the K^+ and Na^+ ions react with OH^- ions, the reaction being supported by electron supply of the DC power source.

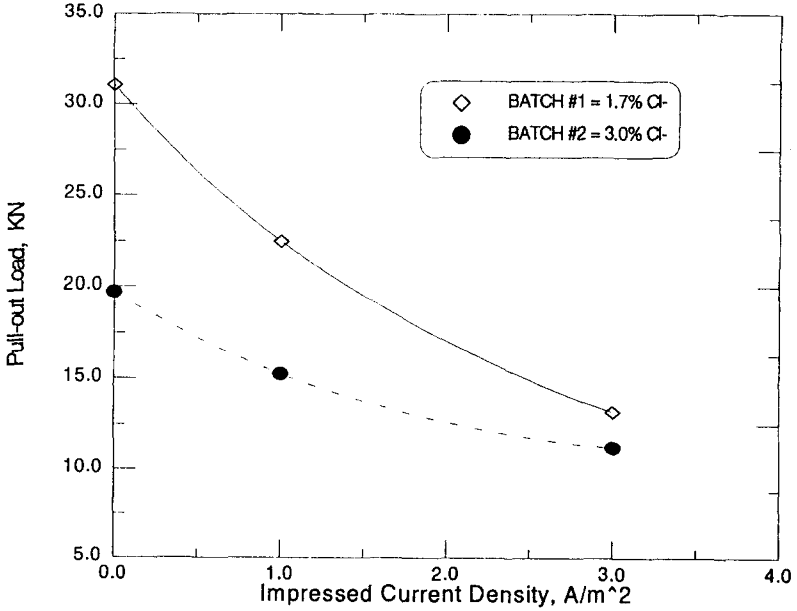

FIG. 5.
Degradation of ultimate pull-out loads.

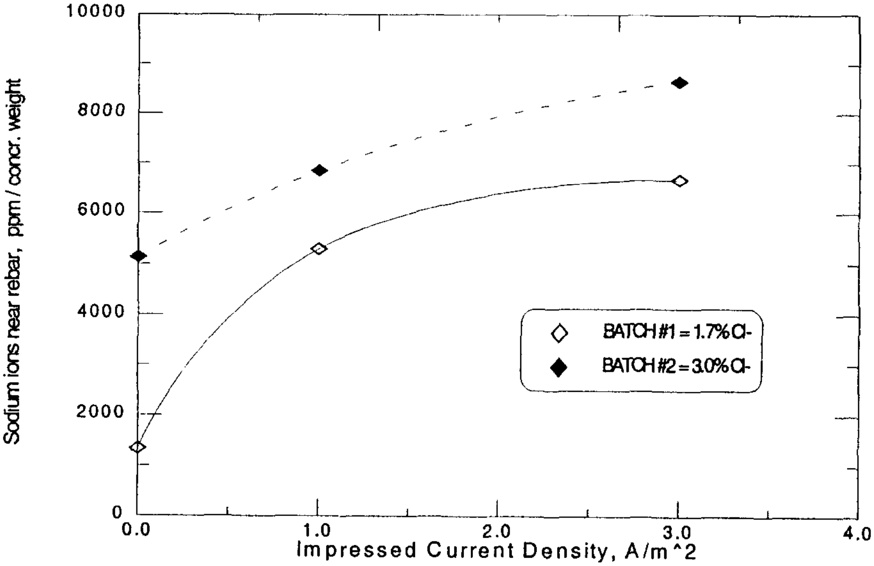

FIG. 6.
Sodium ion concentration nears rebars.

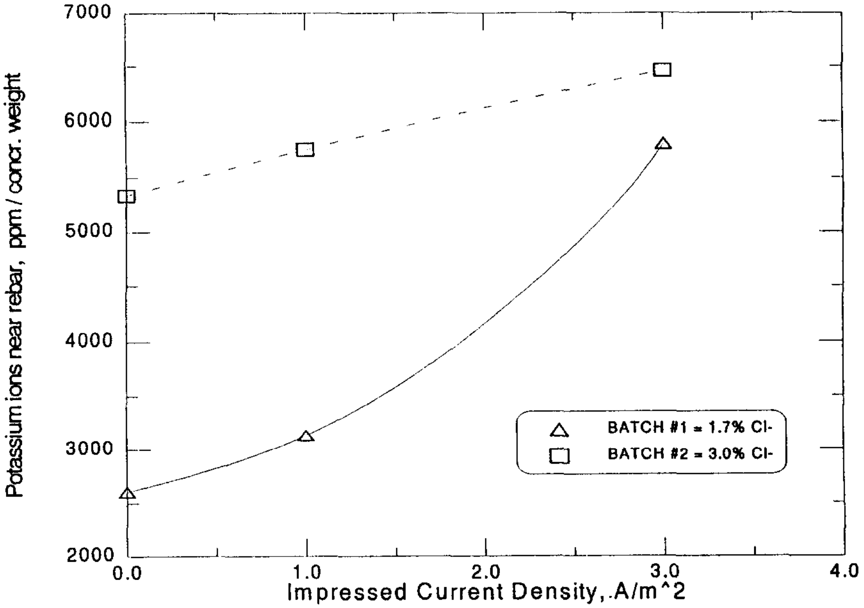

FIG. 7.
Potassium ion concentration near rebars.

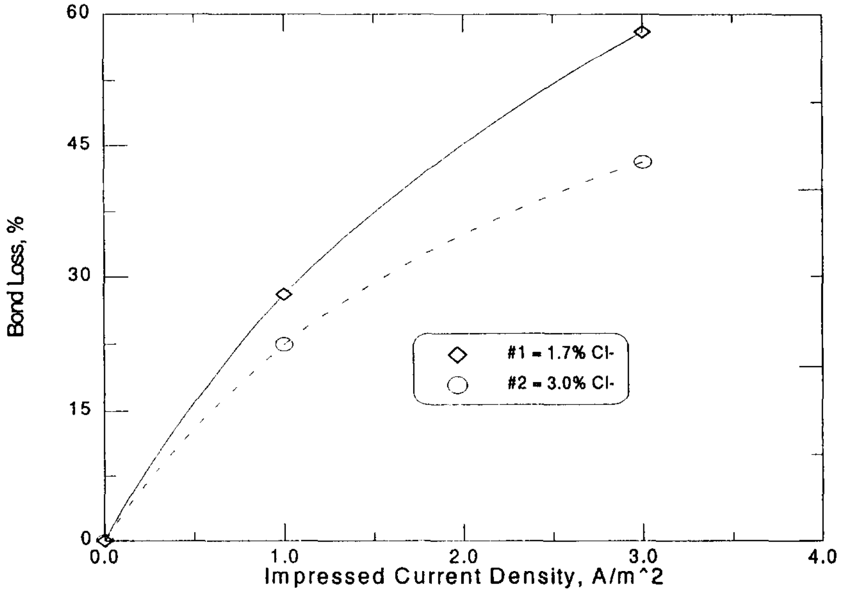

FIG. 8.
Effect of impressed current density on bond loss.

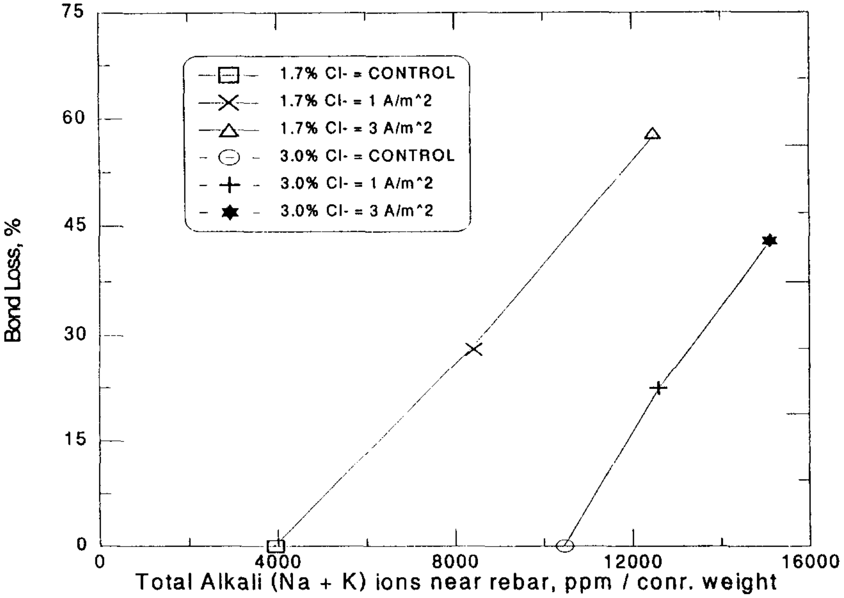

FIG. 9.
Influence of total alkai ions on bond loss.

Figure 4 shows the chloride concentration near the rebars for both concrete batches which were treated at different current densities. Extraction in all test specimens is observed to shift scale with degree of initial contamination and/or applied electric current density. The average reductions in residual chloride contents, at an impressed current density of 3.0 A/m^2, were about 70% in batch #1 (1.7% initial Cl$^-$) and 85% in batch #2 (3.0% initial Cl$^-$) based on chloride contents of control specimens. Such a high difference in chloride reduction is found only in specimens of concrete batch #2 which is predictable due to the higher removal efficiency than from those of batch #1. The greater reductions in specimens treated at a current density of 3.0 A/m^2 compared with 1.0 A/m^2, which reflects their electric charge consumption is directly related to initial contamination levels. Again the differences in ion mobilities could well be the controlling factor in the proportion of total applied electric charge available for migration. The pull-out loads reduced in similar ratio with respect to the control specimens (as shown in Figure 5), averaging about 58% in concrete batch #1 specimens treated at 3.0 A/m^2 compared with 28% for an impressed current density of 1.0 A/m^2. Concrete batch #2 specimens shows much different pull-out load degradation with about 43% loss in bond strength for 3.0 A/m^2 and 22% for 1.0 A/m^2.

In Figures 6 and 7, the concentration of alkali ions (Na$^+$ and K$^+$) around the cathodic steel rebars were somewhat in proportion to the applied current density and shows an inverse relationship to the residual Cl$^-$ ion contents. From electrochemical considerations, an increased cation accumulation around the cathode region enhances damage to cement paste phase since alkali ions such as Na$^+$ and K$^+$ ions tend to electromigrate heavily solvated with a sheath of water molecules because of their small ionic radii [8,9]. The formation of alkali hydroxides during electrochemical extraction is also known to initiate concrete softening by substantially increasing the solubility of the cement silicate hydrates [6,8,10], a principal cement binder of the hydrate form. Due to the high concentration of these alkali metals around the concrete-steel interface and coupled with the wetness associated with their electro-migration, it becomes easier for the resulting cement paste deterioration around the steel rebars to cause disbondment. It is also possible for water molecules to be reduced during ionic migration especially around the steel-concrete interface as water is hydrolysed by cathodic action (Equation 1), and in addition to the inhomogeneities in concrete, differential wet conditions can be sustained [11].

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

The aggressive nature of the high alkaline phase that is caused by the cation electromigration can adversely affect some aggregate rock types. Rock aggregate types prone to attack include porous limestone, shales and cherts, and these are often found in sufficient quantities in the fine aggregate component of concrete. Previous studies have shown such physical and chemical alteration of the aggregate components of the concrete-steel region in ECE treated structures which was identified by their darker appearance [4], and increased porosity [11]. Such deterioration of concrete components can also affect the bond of steel to concrete. It is necessary to stress that the different concrete batching approach adopted in this study had no significant effect on the concrete compressive strengths. The 28th day compressive strengths of the concrete batches ranged from 33 MPa to 36 MPa, and a strength variation of about 3 MPa of average values at the time of ECE application is well within normal expectation.

Pull-out tests show different ECE impact depending on either the initial chloride contamination or impressed (cathodic) current density. In absolute terms, r.c. specimens electrochemically treated with an impressed current density of 3.0 A/m^2 consistently shows increased degradation in bond strength and rebar slippage compared with specimens impressed with a lower current density of about 1.0 A/m^2. Figures 8 and 9 show the variation of bond loss

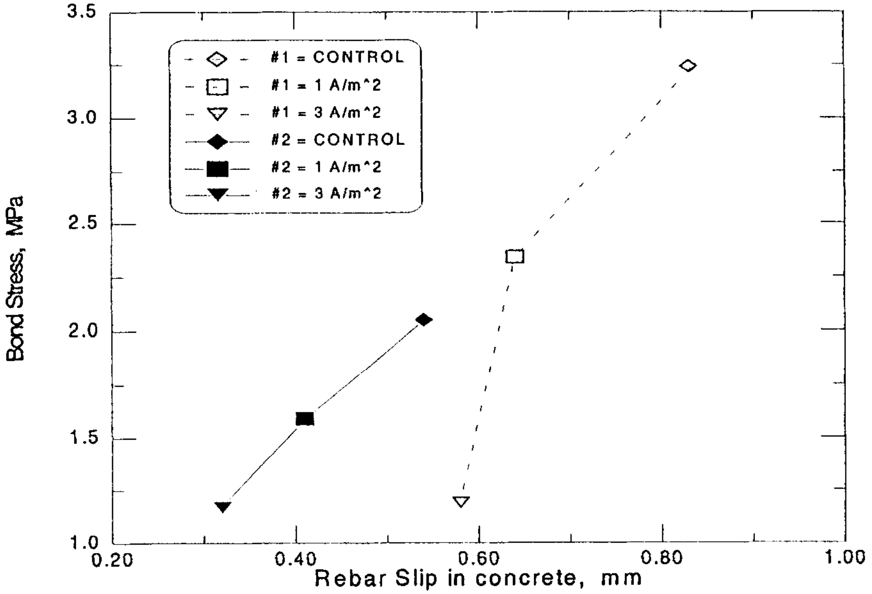

FIG. 10.
Bond stress vs. slip at different ECE states.

with both impressed (cathodic) current densities and total alkali ion contents of the concrete-steel interface. Bond loss calculations were based on differential bond stress values of both ECE treated concrete groups with their control specimens for each chloride contamination level. ECE specimens prepared with concrete batch #1 and premixed with smaller chloride ion concentration shows increased bond loss with impressed current density, although the total alkali ion contents were consistently lower than levels of specimens of concrete batch #2. In absolute terms, the bond stress values for concrete batch #1 were higher than batch #2 for all impressed current densities used in the study. It is suspected the lower concentration of alkali ions around the cathodically polarized steel rebars of concrete batch #1 is indicative of the dissolved ions in the concrete pore structure available to carry the electrical charge thereby resulting in the observed disbondment and probable heating damage. It is noted that the greater loss of bond strength for the concrete with the smaller initial chloride contamination at both current densities could have structural implications. This leads to the speculation that an inadvertent ECE application to chloride-free concrete could lead to very significant loss in bond strength. This condition is presently being investigated by the ECE treatment of concrete specimens containing no admixed chlorides.

Previous studies have used average bond stress versus rebar slippage in concrete to characterize the relative bond strength of the concrete-steel interface [6,12]. Using such indexing factor, extraction of chlorides allowed an easier pull out of embedded steel rebars in the test specimens especially in high contamination concretes. Rebar slippage in concrete was higher at the ultimate bond stress for low chloride contamination specimens. This is the case at all impressed current densities including the corresponding reduction in pull out loads as shown in Figures 10 and 11. Slip initiation occurred at lower load levels before reaching ultimate bond

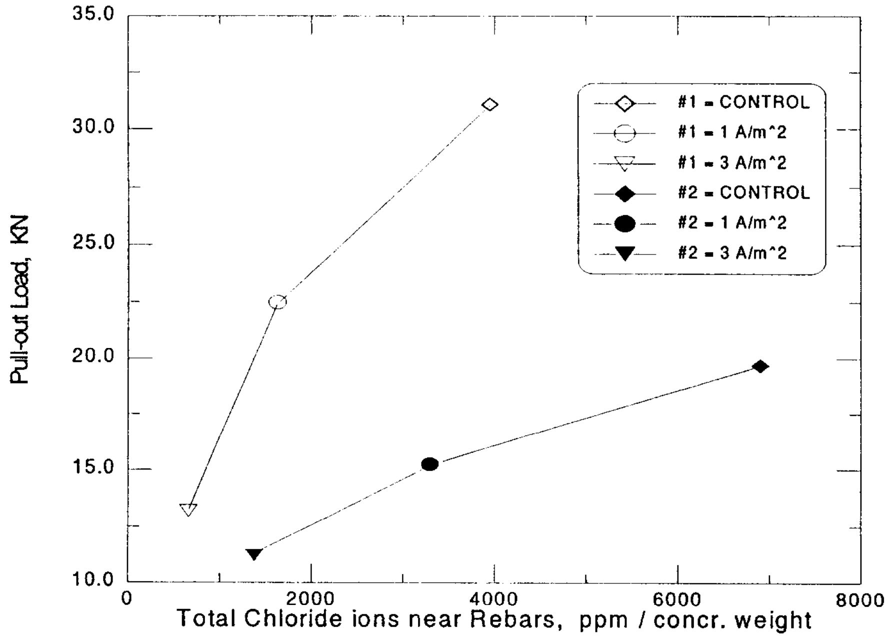

FIG. 11.
Influence of total chlorides on pull-out loads.

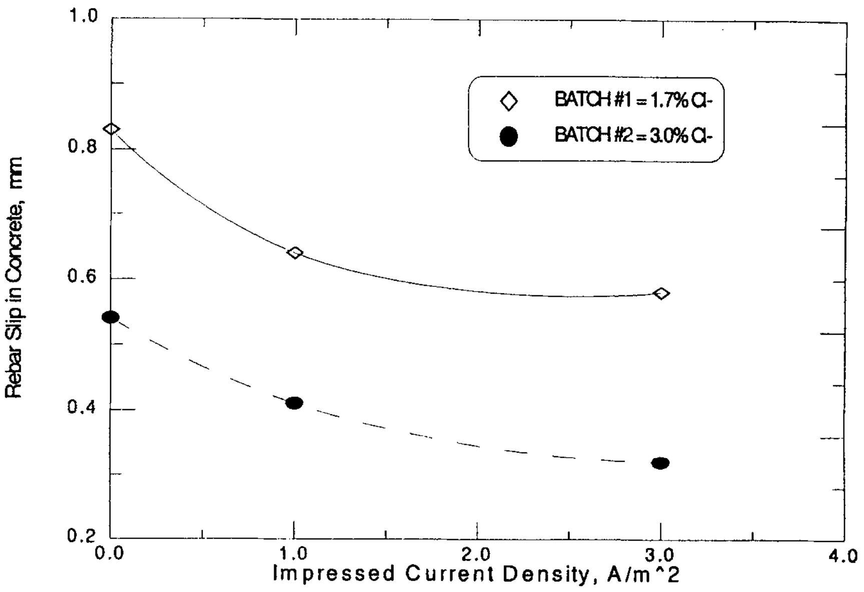

FIG. 12.
Degradation of rebar slip in concrete.

failure in concrete specimens impressed with higher cathodic current densities, although the effect of admixed chlorides was not as pronounced. Also, the higher total alkali ion contents of concrete batch #2 could have adverse consequences, as could the higher impressed current density for both types of concrete.

It is possible that ECE application may have provoked interface degradation due to evolution of hydrogen gas. Although oxygen reduction is the predominant cathodic reaction at the steel-concrete interface, hydrogen generation can also occur because of the level of cathodic polarization of the rebars. In most cases, the applied potential of rebars during ECE is forced into the region below the theoretical "hydrogen line" (i.e., line "a") on the Pourbaix diagram [13]. Pourbaix diagrams are plots of electrochemical potential against pH of metals in aqueous solutions, and are used to determine the electrochemical behaviour of a metal. Studies of cathodic protection of reinforced concrete have reported hydrogen evolution when applied potential of steel is more negative than -1000 mV SCE [14,15], which is applicable to the ECE process. In addition to the Equation 1, some other cathodic reactions at the steel-concrete interface during the ECE application that sustain hydrogen generation include the following;

$$\begin{aligned} 2H^+ + 2e^- &\rightarrow 2H \\ 2H &\rightarrow H_2 \end{aligned} \tag{2}$$

Most of these discharged atomic hydrogen recombines to form molecular hydrogen and leaves the reinforcing steel surface. Although a small portion of the discharged hydrogen is absorbed into the steel, it is the hydrogen evolution reaction that contributes to disbondment.

As the rebar slippage in concrete at the ultimate load levels reduced with impressed current densities (Figure 12) the total residual chlorides also reduced around the steel-concrete interface. The trend is similar to the observed degradation of bond depending on the concrete

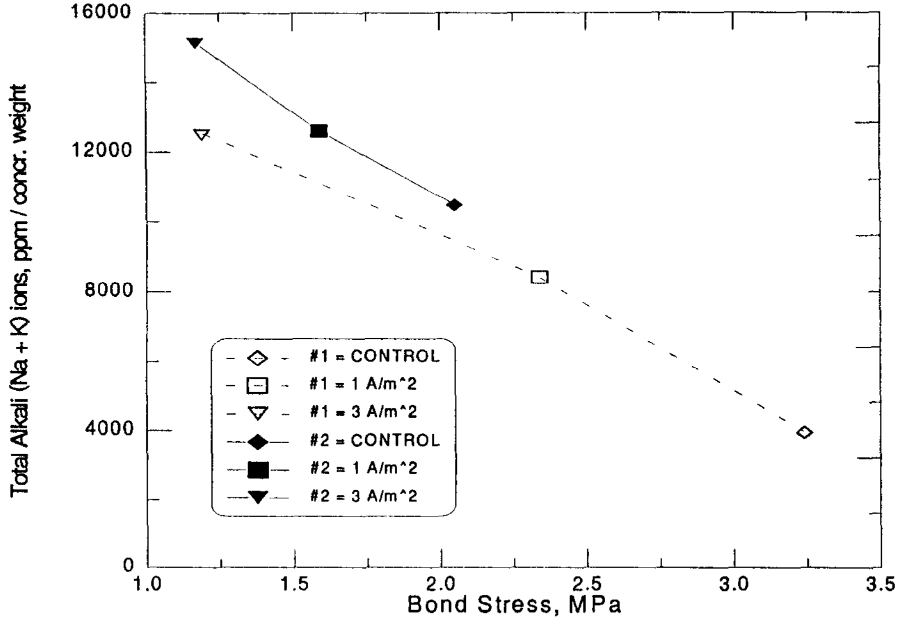

FIG. 13.
Effect of total alkali ions near rebars on bond stress.

contamination. The degree of bond loss between concrete and steel as a result of the electrochemical treatment is indicative of the situation which can result from an in-situ application of the process to a field structure. It is instructive that the increase in total alkali ion concentrations of the cathodic region can either be beneficial as rebar corrosion is controlled or, denote an altered interface as disbondment leads to structural failure. As shown in Figure 13, increased accumulation of total alkali ions around the concrete-steel regions resulted in lower bond stress as the impressed current density increased. The influence of admixed chlorides on both bond reduction and increases in total alkali ions is comparable. ECE specimens premixed with 3.0% Cl^- ions experienced lower reductions in bond strength and increased total alkali ions than specimens premixed with 1.7% Cl^- ions. The practical effect of the level of impressed cathodic current densities used in this study is the significant changes in macrostructure and interface behaviour observed as chloride contamination increased.

Physical inspection of the concrete-steel interface of the electrochemically treated specimens shows an accumulation of whitish deposits around the rebars treated at high impressed cathodic current densities. The deposits were spread over more of the rebar surface area in concrete batch #1 (Figure 14) than in batch #2 (Figure 15), and increased with impressed cathodic current density. In general, the coverage was substantially higher for the specimens treated at a current density of 3.0 A/m^2 than for lower impressed current densities. Control specimens of both concrete batches were substantially corroded as one would expect in chloride contaminated concrete. It is believed the whitish deposits are due to the alkali hydroxides formed as a result of cathodic action during ECE application, and which have direct effect on rebar repassivation. It is reported that a consequence of cation (in this case Na^+ and K^+) electro-migration is the ability to reduce the solubility of $Ca(OH)_2$ in the cement matrix, and SEM studies have

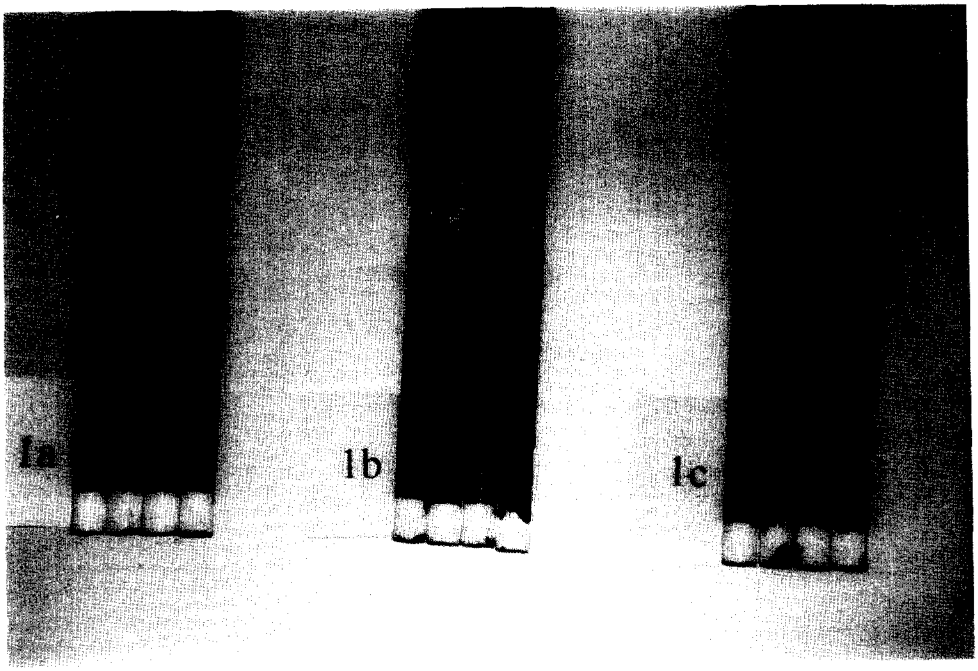

FIG. 14.
Rebars recovered from ECE concrete batch #1 (a - control specimens; b - specimens treated at 1 a/m^2; c - specimens treated at 3 A/m^2.

confirmed features of redistribution of $Ca(OH)_2$ in the pore fluid during ECE studies [11]. Another explanation for the disparity in coverage of the whitish deposits could be their different ECE efficiencies. An efficient desalination achieved at the higher impressed current densities would mean a better alkaline hydroxide formation. From electrochemistry, the higher transport number of the OH^- ions as shown in Table 3, will influence the formation of such hydroxides. These ion mobilities are typical for concrete media at 25°C and indicate observed patterns of electric charge distribution during ECE studies [8,16].

However, since a high degree of desalination is achieved in the ECE application, while discounting the accompanied risk of bond loss, prospects of rebar corrosion is clearly minimized. The substantial accumulations of total alkali ions as well as the reduced levels of residual chlorides would be expected to contribute immensely to the development and maintenance of passive conditions around reinforcing steel. An important inference from this study is that an electrochemical treatment of steel reinforced concrete based on a practical

TABLE 3

Ion Mobilities in Concrete ($\times 10^{-4} cm^2 V^{-1} s^{-1}$)

Ion	Cl^-	OH^-	Na^+	Ca^{2+}	K^+	H^+
λ_o	7.91	20.5	5.19	5.95	7.62	34.9

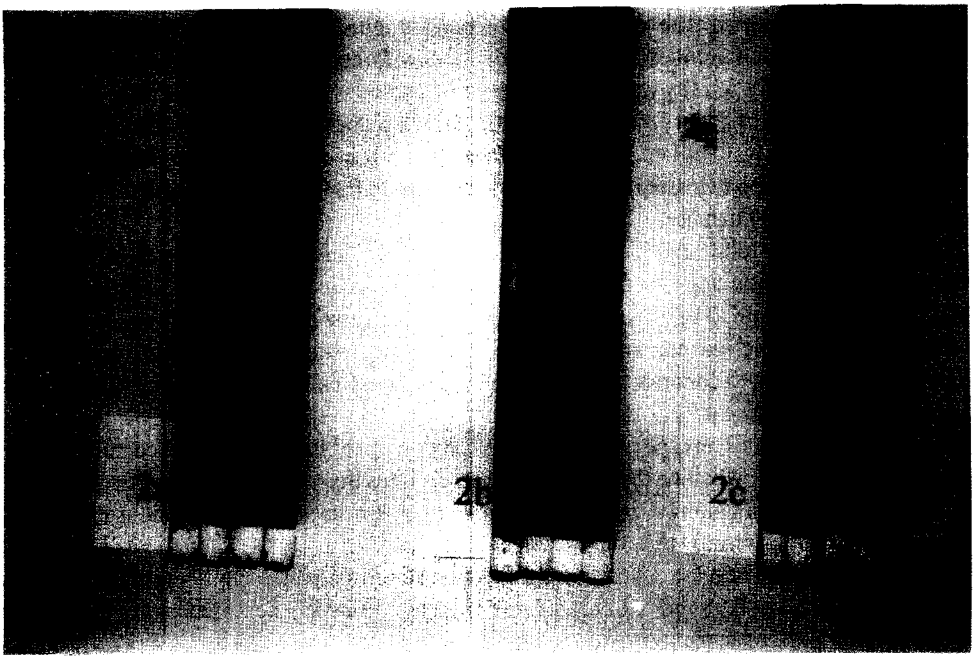

FIG. 15.
Rebars recovered from ECE concrete batch #2 (a - control specimens; b - specimens treated at 1 A/m^2; c - specimens treated at 3 A/m^2).

impressed current density of about 1.0 A/m^2 appears likely to provoke alteration of the cement paste macrostructure. When higher applied current densities are used, ECE application shows significant degradation of the concrete's mechanical properties especially around the reinforcing steel interface. Hence any application of ECE to concrete containing pretensioned tendons holds greater risk of severe structural damage in addition to a significant possibility of hydrogen embrittlement. In relation to structural integrity, the observed reductions in bond stress and rebar slippage are clearly pronounced even in the laboratory concrete specimens. In practice, there are probable variabilities inherent in concreting from different batches as well as the contributory effects of the concrete's inhomogeneity. On the other hand, a practical limitation of the investigation is that a good number of candidate concrete structures are designed to have their reinforcements resist flexure, placing an additional requirement on supplemental evaluation to ascertain comparable structural behaviour. Moreover, the use of plain steel rebars in this study clearly discounts any beneficial influence of shear deformation and lugs on the steel as would have been the case where deformed rebars used.

Summary

1. The interface mechanical properties of reinforced concrete are found to be adversely affected by application of ECE. As an index of concrete-steel degradation, average bond stress versus rebar slippage shows consistent reductions when chloride ion contaminated concrete is subjected to electrochemical treatment.

2. Bond losses are increased as the impressed current density used in electrochemical chloride extraction is also increased. The adverse effect on bond is somewhat dependent on the degree of initial chloride ion contamination of the candidate reinforced concrete. Concrete specimens premixed with 1.7% Cl^- ion (by weight of cement) and treated with 3.0 A/m^2 of cathodic current exhibited bond losses of about 58% of the controls, which reduced to about one-half when a third of the current density was applied. Similar ECE applications to concrete contaminated with 3% Cl^- ions experi-enced bond losses of about 43% at the high current density dropping to half at the lower cathodic current density.
3. Accumulation of 'total' alkali ions (mainly Na^+ and K^+) around the concrete-steel region during ECE application appears detrimental to the interface integrity. Increases in the alkali concentrations are found to be directly dependent on the impressed current density as well as the initial degree of concrete contamination. Disbondment associated with these alkalies in electrochemically treated concrete could counteract the beneficial features such as aiding rebar repassivation.
4. Bond reductions in all test specimens operated at a practical ECE impressed current density of about 1.0 A/m^2 are lower than those caused by three times that current density irrespective of the chloride ion contamination. A substantial percentage decrease (~50%) in bond is associated with such changes in impressed cathodic current densities.
5. The observed changes at the concrete-steel interface suggest adverse implications of the ECE process on the structural durability of candidate concrete when such electrochemical treatments are based on impressed current densities over 1.0 A/m^2 of concrete surface.

Acknowledgement

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