

論文

[1137] Electrochemical Methods for Rehabilitation of Corroding Steel in Concrete in USA

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1. INTRODUCTION

Corrosion is recognized today as one of the major contributors to the deterioration of steel reinforced concrete structures. The presence of chlorides, introduced by deicing salt, set accelerators or seawater, is a major contributor to corrosion of steel in concrete. The only proven means of stopping this corrosion without removal of the chloride contaminated concrete are electrochemical chloride removal and cathodic protection [1]. Strategic Highway Research Program (SHRP) Contracts C-102A and C-102D were designed to study the techniques of chloride removal and cathodic protection, respectively. This paper summarizes the work done under these contracts.

2. CHLORIDE REMOVAL

Electrochemical chloride removal was first investigated in concrete in the mid 1970s and was recently studied under Strategic Highway Research Program contract [2]. This process is accomplished by placing an anode at the surface of the concrete and passing a direct current between the anode and the reinforcing steel, which serves as a cathode. Since anions migrate toward the anode, chloride ions migrate toward the surface of the concrete, and much of the chloride can be made to exit the concrete completely. Assuming that all of the current was carried by chloride ions, then 96,500 coulombs would remove 35.5 grams of chloride. Removal efficiency is defined as the amount of chloride actually removed divided by this theoretical amount. The amount of chloride which is removed depends on chloride concentration, chloride distribution, current and total applied charge.

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Slabs measuring 60 x 60 cm were constructed with a double mat of reinforcing steel using Class C bridge deck concrete with 0.50 water-cement ratio and 6.0% air content [2]. The slabs were heavily contaminated with cast-in chloride, up to 2.4% by weight of cement. The amount of chloride removed was incomplete, and the technical target of 70% removal not met. Even very heavy treatments removed only 40-55% of the total chloride present. Figure 1 shows the current efficiency for chloride removal as a function of total charge passed. It is interesting to note that the current efficiency of chloride removal from all the slabs was equal regardless of current density. It can be seen on Figure 1 that at the beginning of the process current efficiency is about 40%. Efficiencies decrease as treatment progresses. After about 350-500 coulombs/sq.cm., efficiency is quite low and there is little advantage to continuing the treatment beyond this point. From these data it can be concluded that overall current efficiency of the process can be expected to be about 20%. In other words, the passage of 96,500 coulombs of charge will remove about 7 gram of chloride.

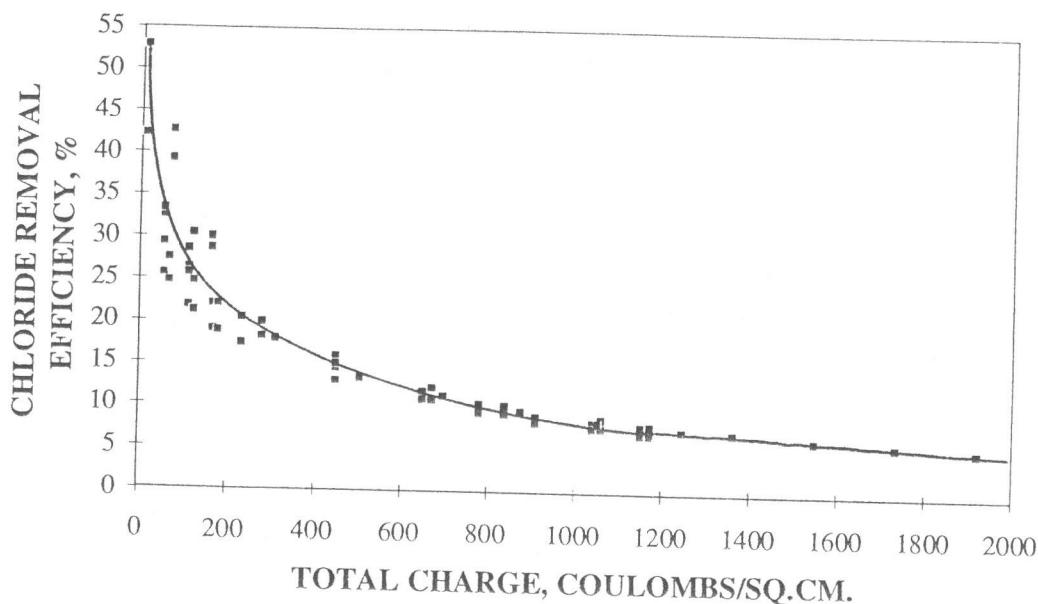


Figure 1. Overall Current Efficiency vs. Total Charge for Test Slabs.

Although the amount of chloride removed was incomplete, further tests indicated that more complete removal may be unnecessary. Chloride analysis of concrete adjacent to the steel after treatment ranged from only 0.2 to 0.4% by weight of cement. This was determined by coring the slabs, collecting powder samples by drilling parallel to the reinforcing bars, and analyzing for total chloride by the AASHTO T 260 method. Chloride which remained in the concrete was positioned primarily between and behind reinforcing bars. This chloride showed little tendency to remigrate during 40 months of monitoring.

Another benefit of the chloride removal process is the generation of alkalinity around the reinforcing bars. This occurs because of the cathodic reaction, which generates one mole of hydroxide ion for each 96,500 coulombs of charge passed. This plays an important role in arresting corrosion, since the rate of corrosion is more dependent on chloride/hydroxide ratio than on chloride concentration alone.

The effectiveness of the treatment was demonstrated by half-cell potential and macrocell current measurements. Half-cell potentials of the steel in the control slab (which was not treated) were very corrosive, whereas potentials of the steel in all treated slabs were very non-corrosive, regardless of the degree of treatment. The corrosion macrocell current (corrosion current flowing between the top and bottom mats of steel) was reduced from an average of 0.42 milliamperes to very near zero by the treatment. Forty months after treatment, steel potentials remain non-corrosive and macrocell currents indicate little tendency to return to corrosive conditions. Figure 2 shows the development of corrosion macrocell charge of treated slabs. As shown on the figure, the control slab cracked due to corrosion after 7 coulombs/sq.cm. of charge. During this same period of time the treated slabs accumulated only 5.0 coulombs/sq.cm. of charge. Visual inspection at the end of the study showed the bars from the control slab to be heavily corroded, whereas the bars from the treated slabs showed only slight rusting.

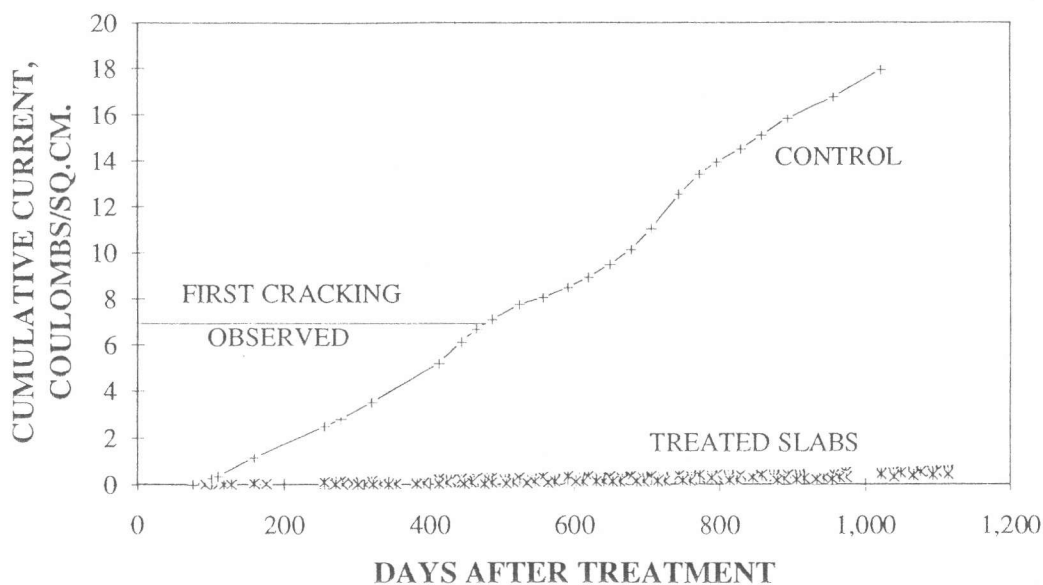


Figure 2. Cumulative Macrocell Corrosion Charge vs. Time.

Several other concerns which arise as a result of the passage of large amounts of current through concrete were also studied. Reinforcing steel bond strength was measured over the full range of current and charge applied for both chloride removal and cathodic protection. The application of a very high current (50 amperes/sq.meter) and/or high amount of total charge (720 coulombs/sq.cm.) did result in a reduction of bond strength and damage to the slab. The proper use of the current and charge now recommended for both chloride removal and cathodic protection had no adverse effect, however.

The possible hydrogen embrittlement of conventional reinforcing steel was also studied. Although a slight temporary loss of ductility was noted on smooth steel specimens, this loss was determined to be not structurally significant. However, the process of chloride removal, which results in the generation of atomic hydrogen at the steel surface, is **not** recommended for members containing high strength prestressed steel.

Based on these laboratory and test yard results, a chloride removal process was defined which results in effective removal of chloride without damage to the concrete or reinforcing steel. Current density was limited to less than 5 amperes/sq.meter. System voltage was limited to less than 50 volts for safety reasons. Under these conditions, treatment time for chloride removal can be expected to be 2-6 weeks. Typical applied charge was 300-450 coulombs/sq.cm. Treatment times and charges greater than these will probably yield little additional benefit. The system developed consists of a catalyzed titanium anode, which was applied to the surface of the concrete together with a blanket material which served to contain the electrolyte. The anode/blanket composite was fixed to the outer surface of the structure, and was prefabricated for standard bridge members. The blanket was kept wet with electrolyte solution during the treatment process. A 0.3 molar sodium borate buffer electrolyte was used to maintain pH high and therefore prevent the evolution of chlorine gas.

After the laboratory and test yard phases of the contract, field validation studies were successfully conducted on four structures. Field trials were carried out on a bridge deck in Ohio, and substructures in Florida, New York and Ontario [3].

3. CATHODIC PROTECTION

Cathodic protection is an effective technique of corrosion control for metals exposed to an electrolyte. In the early 1970s it was recognized that concrete is an electrolyte and is capable of supporting a small flow of electric current. It was further recognized that this current could be used to polarize the reinforcing steel in the cathodic direction, and thus mitigate the corrosion process. A 1988-89 survey [4] indicated that more than 275 bridge structures in North America had been cathodically protected.

Laboratory studies were first conducted to establish the corrosion rate of cathodically protected steel as a function of salt concentration, pH, temperature and polarization. Experiments were conducted in a packed bed of sand wetted with simulated pore water solution. This procedure had the advantages that solution chemistry could be carefully controlled, corrosion current and potential could be easily measured, oxygen was readily available to the steel, and the specimen could be easily weighed to establish corrosion rate. These studies are detailed in a recent publication [5].

Corrosion rate was found to be very sensitive to chloride concentration, pH and cathodic current. An increase of one unit of pH was found to decrease the rate of corrosion over an order of magnitude. The application of cathodic protection was found to arrest corrosion at any of the conditions studied. Figure 3 shows the effectiveness of cathodic protection at a chloride concentration equivalent to 4.8% by weight of cement.

Results from the corrosion studies were then used to determine the amount of polarization needed to achieve an acceptable rate of corrosion (<2.5 micron/year). Although the exact amount of polarization needed was a complex function of many variables, a polarization of 150 mV was found to be generally acceptable. Because of the complexity of polarization-based criteria, attention was then focused on simpler current-based criteria.

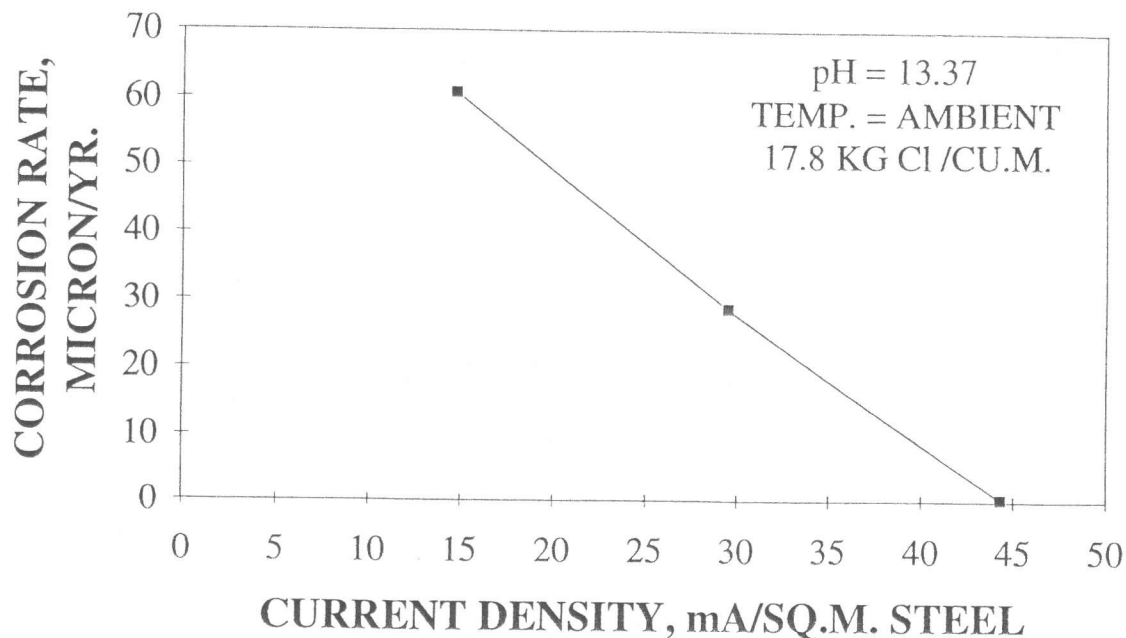


Figure 3. Corrosion Rate vs. Cathodic Protection Current Density

When cathodic protection current is passed through concrete, chloride ions migrate away from the steel surface and hydroxide ions concentrate there. Both of these actions lessen the corrosion rate of the steel. In this study a mathematical model was used to predict the movement of ions through concrete [6]. The effects of several variables, such as chloride concentration, chloride distribution, pH, current density and temperature were examined. All of these variables were found to have a significant effect on the chloride/hydroxide ratio, and therefore on the corrosive state of the steel. The concentration gradients which develop as current is passed result in a decreasing current requirement with time. One example of this decrease is shown by the following table. This example was for severely contaminated concrete, 4.0% average chloride by weight of cement in the concrete cover, and 1.6 % chloride at the steel surface. The current required was calculated to achieve a corrosion rate of <2.5 micron/year.

<u>Time-on-line</u>	<u>Current Required</u>
Start-up	54 milliamps/sq.meter
1 month	22 milliamps/sq.meter
3 months	17 milliamps/sq.meter
12 months	17 milliamps/sq.meter

The current required was found to correlate well with chloride concentration. This suggests a simple current-based criterion in which the applied current is related to analysis of the concrete at the level of the steel reinforcement. The current applied is based on that required after equilibrium conditions are reached. Chloride analysis should be conducted at the most contaminated (most corrosive) site in the cathodic protection zone. The relationship between chloride concentration at the steel and current required is shown on Figure 4. A slightly higher current should be applied to include a margin of safety.

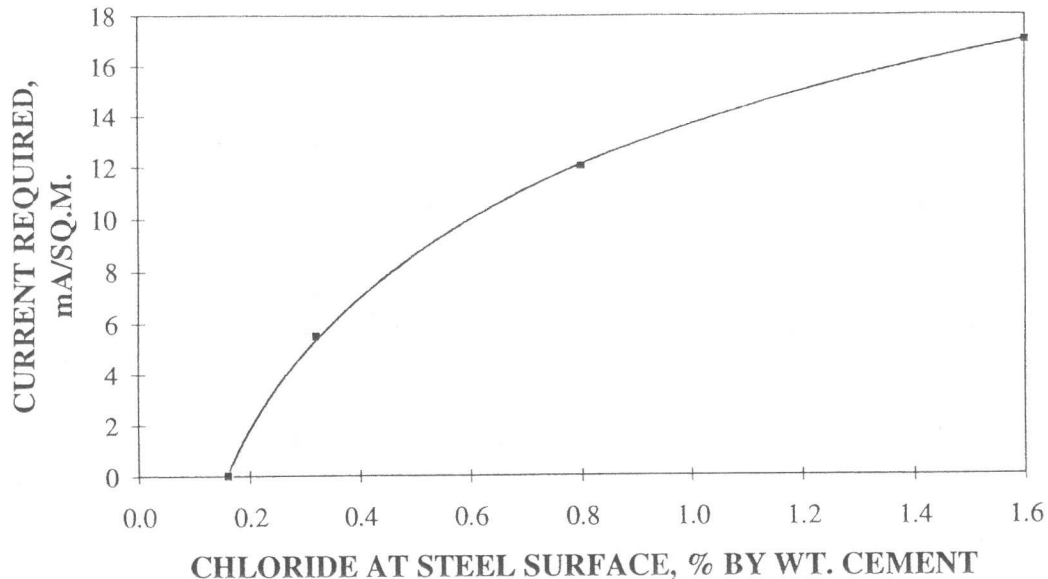


Figure 4. Cathodic Protection Current vs. Salt Concentration.

4. CONCLUSIONS

The chloride removal process was found to be an effective technique for controlling corrosion in chloride contaminated concrete. The process should not be used on structures containing prestressed steel. It should be used with caution where alkali reactive aggregates are present because of the large amount of alkalinity generated. The time for which the treatment is effective is not yet established.

Cathodic protection was found to be a highly effective technique for arresting corrosion in reinforced concrete structures. A polarization of 150 mV was found to be generally acceptable for controlling corrosion to an acceptable level. Another simple criterion based on the level of chloride contamination is suggested.

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