Investigation of Electrical Effects on Alkali-Aggregate Reaction

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ABSTRACT

The incidence of ASR in structures such as precast electrical trans-
mission poles and the bases and foundations of electrical equipment has
raised the question of a possible effect of electrical fields on ASR. This
question has been raised again as it pertains to the application of cathodic
protection systems to reinforcing steel in bridge decks and substructures.
If Alkali-Silica Reaction can be influenced by electric current or potential
difference, then the application of cathodic protection to control corrosion
of the reinforcing steel could initiate or accelerate ASR. Research funded
by the National Science Foundation is currently in progress at Cornell
University to investigate this question.

The experimental program includes mortar-bar expansion tests with and with-
out applied current, measurements of the rate of diffusion of sodium and
potassium ions through concrete influenced by a potential difference, and a
small scale cathodic protection installation.

SECTION 1: INTRODUCTION

A causal relationship between the presence of an electrical field in or
near a reinforced concrete structure and the development of Alkali-
Aggregate Reaction (AAR) has been suggested by the observation of AAR in the
foundations of electrical transmission towers and precast concrete power
poles (Hobbs 1985, Slate 1982), but conclusive results have not been pre-
sented. Resolution of this issue has become important with the increased
use of impressed current cathodic protection systems for the control of the
corrosion of reinforcing steel in concrete.

One of the major problems in the deterioration of infrastructure in
North America and Europe is the corrosion of reinforcing steel in concrete
structures. Cathodic protection, by means of an impressed current, has been
found to be one of the most effective means of controlling this corrosion.
In this method, a voltage source and external anodes are used to negatively
charge the steel. As will be discussed, this negative charge attracts
alkali ions towards the steel, rapidly increasing the local alkali concentra-
tion, relative to the levels at which AAR normally occurs.

The primary hypotheses of the research now in progress are:

1.   Diffusion of alkali ions under the influence of an electrical potential gradient may accelerate alkali-aggregate reaction.

2.   An increased concentration of alkali ions in the vicinity of cathodically protected reinforcing steel may initiate AAR under conditions which would normally have been considered to be innocuous.

An experimental program is now in progress at Cornell University to test the above hypotheses. This program is briefly described in the following paper, but due to the preliminary nature of the work conducted to date, results are not yet available.

SECTION 2: CORROSION OF REINFORCING STEEL AND CATHODIC PROTECTION.

Corrosion is an electrochemical process ie., it is a chemical reaction involving the transfer of charge from one species to another. For such a reaction to occur there must be two half cell reactions: one capable of producing electrons (the anodic reaction occurring at the anode) and one capable of consuming electrons (the cathodic reaction occurring at the cathode). Moreover there must be an electrical connection between the anode and the cathode. The anode, cathode, electrolyte and the external circuit form the electrochemical cell.

For steel embedded in concrete, both micro and macro cells occur as shown schematically in Figure 1. Steel in uncontaminated concrete will
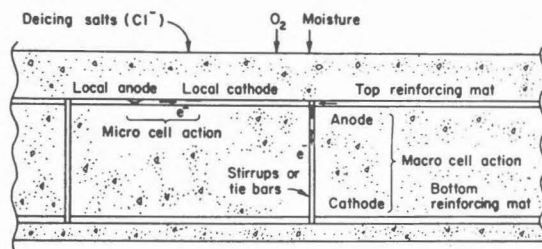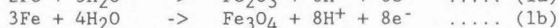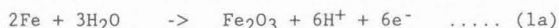

Figure 1.   Corrosion of Steel in Concrete by Micro- and Macro-cells

initially develop a thin oxide layer which is stable in the high pH environment. This layer prevents corrosion of steel and is called the "passive oxide film." Under the action of chloride ions and/or carbonation, the passive layer is broken at several locations along the top reinforcing mat and corrosion is initiated at these local anodes. The adjacent areas of the steel bar which have retained an intact passive layer act as local cathodes. The pore solution serves as the electrolyte and the steel bar itself completes the external circuit between the anodes and cathodes. The bottom reinforcing mat (if any) normally has the oxide layer intact and can act as a large cathode relative to the more anodic upper mat. Both micro and macro cells operate simultaneously. Under normal conditions in concrete the following reactions occur:

Anodic reactions:

$$2Fe + 3H_2O \quad -> \quad Fe_2O_3 + 6H^+ + 6e^- \quad \ldots\ldots \text{ (1a)}$$
$$3Fe + 4H_2O \quad -> \quad Fe_3O_4 + 8H^+ + 8e^- \quad \ldots\ldots \text{ (1b)}$$

Cathodic reaction:

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^- \quad \ldots\ldots (2a)$$

The corrosion process can be stopped by applying a voltage difference between the anode and cathode which is opposite in sign to the natural potential of the electrochemical cell. Electrons are supplied to the anode and removed from the cathode. This is the principle of cathodic protection.

If the electron source is an external battery or power supply, the method is referred to as impressed current cathodic protection (CP). In reinforced concrete it is impractical to connect multiple external power supplies between local anodes and cathodes. Therefore electrons are supplied to the entire reinforcing assembly using external anodes (see Figure 2). Under CP the entire reinforcing mat becomes the cathode. Since the electrical potential of the cell is altered by the application of the CP, the reaction at the cathode can be either equation 2a (above) or at higher electrical potentials:

$$2H^+ + 2e^- \rightarrow H_2 (g) \quad \ldots\ldots (2b)$$
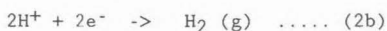
The description given above is only a brief summary of the processes of corrosion and cathodic protection. Details of the application of cathodic protection to reinforcing steel in concrete are beyond the scope of this brief paper, but are found in the paper and bibliography by Hover (1985).
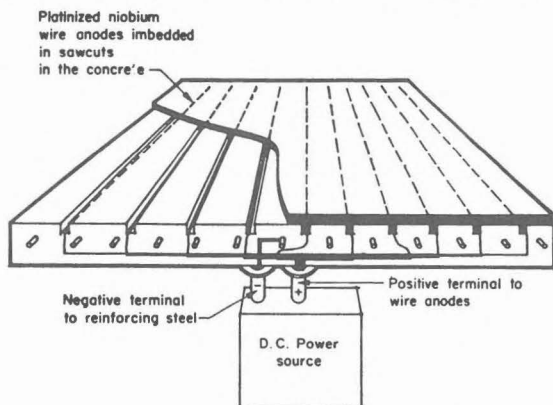

Figure 2.   Distributed Linear Anode Method of Cathodic Protection

Of particular interest in the present research is the fact that the steel mat is negatively charged as a result of the application of cathodic protection. Pore solution studies by Diamond (1983) have shown that the major cations present are sodium and potassium and a small amount of calcium.

Locke (1983) observed that positively charged alkali ions in concrete were attracted to cathodically protected reinforcing steel, and that a sodium, potassium, and calcium-rich phase accumulated at the steel/concrete interface. (Locke was concerned about the impact of this alkali accumulation on bond strength.) The concentration of alkali ions therefore increases closer to a cathodically protected steel bar, and the concentration of negatively charged ions, such as Cl- decreases near the bar.

SECTION 3: INFLUENCE OF ELECTRIC FIELD ON AAR

An apparent consensus regarding the mechanism of AAR has recently emerged among various workers in the field (Chatterji et al. 1986, Vivian 1983, Dent Glasser and Kataoka 1981). This consensus holds that only certain silica aggregates are reactive because of their open lattice microstructure. At the molecular level, silica-based aggregates are composed of silicon-oxygen tetrahedra with silicon at the center and oxygen at the four corners. Oxygen atoms at the corner sites of the lattice are shared by adjacent tetrahedra. Furthermore, at the surface of the siliceous aggregate there are a large number of Si-OH groups. It has been found that reactive silica aggregates like opal and chert have a large number of silicon-oxygen bond defects and consequently a more open lattice structure.

It is believed that the OH$^-$ ions in the pore solution attack the silanol (Si-OH) groups and open-up the surface layers to diffusing OH$^-$ ions. The hydroxyl ions then attack the siloxane (Si-O-Si) bridges leading to a further exposure of internal bond defects. The OH$^-$ ions are present in the pore solution which diffuses into the reacting aggregate. The positive counter ions, the alkali ions, are readily available in the pore solution and combine with the newly formed silica micelles to form the amorphous alkali-silica gel. With continued diffusion of the pore solution the gel expands and cracks the confining cement mortar matrix.

Cathodic protection could affect this process in various ways. Under CP there is an electric field imposed on the concrete which causes the positively charged alkali ions to move towards the steel and the negatively charged ions towards the external anodes. It is also well known that the movement of ions is accompanied by a small movement of fluid in the direction of current flow ie., towards the steel (Hampel 1964). The actual rates of the various steps of alkali-silica reaction are unknown. But it seems reasonable to assume that in the presence of a large reservoir of OH$^-$ ions the concentration of alkali ions and the rate of imbibition of pore fluid will control the rate of the overall reaction. Thus CP will reasonably cause the acceleration of ASR in the vicinity of steel. Whether an increase in the rate of the reaction will cause an increase in cracking is debatable. A high concentration of alkali ions would probably lead to alkali rich gels, but the experimental evidence relating chemical composition to swelling capacities is inconclusive. It may be possible that the movement of pore fluid due to the electric field causes a rapid transformation of rigid gel into deformable sol and thus reduce the cracking tendency of the gel. In any case we wish to emphasize that the rate of the chemical reaction itself may increase due to Cathodic protection.

SECTION 4: EXPERIMENTAL ARRANGEMENT AND PROCEDURES

The arrangement consists of 100 mm x 200 mm concrete cylinders with a concentrically cast reinforcing bar (12 mm dia.) arranged in plastic drums as shown schematically in Figure 3. The cylinders are placed in a bed of conductive granulated coke over gravel, and cathodically protected using conductive polymer anodes and an impressed current. The cylinders are kept moist by the evaporation of water through the coke breeze. The experimental variables are alkali content of cement, proportion of reactive aggregate and impressed current density (mA/m^2 of steel surface). Based on preliminary chemical (ASTM C269) and mortar bar tests (ASTM C227) chert was chosen as the reactive aggregate. Nonreactive coarse aggregate used was crushed limestone (12 mm max size). Four, 12 and 20% of the coarser fractions (12 mm to No. 4 sieve) of the limestone aggregate was replaced by crushed chert. Three cements - high, medium and low alkali were used. The alkali contents of the cement were 0.95, 1.7 and 2.8%. Current densities of 0, 40 and 130 mA/m^2
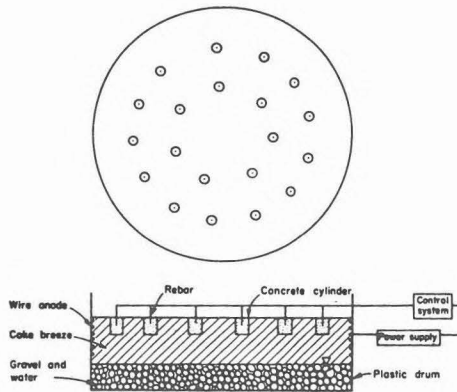
Figure 3.   Experimental Set-up

sq. ft of bar area were impressed on the reinforcing bars. A total of 117
cylinders were cast, 13 per material combination. The cylinders will be
removed periodically and the occurence of ASR products will be studied using
optical and electron microscopy. A limited number of plain cylinders were
also cast in each batch. Some of these cylinders are being instrumented to
measure expansion data. Apart from the ASR products, the electrode poten-
tial, current flow and potential across each of the cylinders will also be
monitored. The experiment was setup in mid July 1986 and is expected to be
run for at least 18 months. Cathodically protected structures in the field
are also being examined for evidence of AAR. A more detailed account will
be reported with the final results.

SECTION 5: CONCLUDING REMARKS

    Based on known evidence, the hypothesis has been presented that the
application of cathodic protection may initiate or accelerate AAR in certain
concretes. It may also be shown that the rate of the chemical reaction
itself is accelerated, independent of the rate of volumetric expansion. If
this hypothesis is proven correct, then it may be necessary to evaluate the
potential for AAR in structures for which cathodic protection is being con-
sidered as a retrofit measure. Average alkali concentrations in the cement
paste which would normally be considered to be innocuous may in fact prove
to be deleterious given the tendency of the cathodic protection to concen-
trate the alkalies in the vicinity of the steel. On the other hand, struc-
tures in which AAR would normally proceed so slowly so as to not be of prac-
tical consequence may experience an accelerated AAR as a result of the appli-
cation of cathodic protection.

REFERENCES:

Chatterji, S. et. al. 1986. Cement & Concrete Research. 16:246-54.

Dent Glasser, L.S., and Kataoka, N. 1981. In 5th Intnl' Conf. on
Alkali-Aggregate Reaction in Concrete, S252/23, Capetown, S. Africa, Natl.
Bldg. Res. Inst.

Diamond, S. 1983. In 6th Intnl' Conf. on Alkalis in Concrete, pp. 155-166, Copenhagen, Denmark, Danish Concrete Association.

Hampel, C.A., ed. 1964. The Encyclopedia of Electrochemistry, pp. 536-37, Reinhold, New York.

Hobbs, D.W. 1985. In Workshop on AAR in Concrete and Deterioration and Rehabilitation of Concrete Parking Structures, Montreal, Canada.

Hover, K.C. 1985. In Rehabilitation, Renovation and Preservation of Concrete and Masonry Structures, ACI SP-85, Amer. Conc. Inst. Detroit.

Locke, C.E. et.al. 1983. In CORROSION 83, Natl. Assoc. of Corrosion Engrs., Houston.

Slate, F. O. 1982. Unpublished report on Alkali-Silica Reaction in Precast Concrete Power Poles, Cornell University, Ithaca.

Vivian, H.E. 1983. In 6th Intnl' Conf. on Alkalis in Concrete, pp. 187-194, Copenhagen, Denmark, Danish Concrete Association.