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# COMBINED EFFECTS OF ALKALI-AGGREGATE REACTION (AAR) AND CATHODIC PROTECTION CURRENTS IN REINFORCED CONCRETE

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### ABSTRACT

The application of electrochemical systems such as impressed-current cathodic protection (CP), to retard the corrosion of the reinforcement in concrete structures, increases the alkalinity of the concrete and may enhance the risk of alkali-aggregate reaction (AAR), if reactive aggregates are present. Four levels of impressed current (0, 25, 50 75 mA/m<sup>2</sup>) were applied to protect steel reinforcement placed in specimens containing four different aggregates and two different alkali levels, in order to assess this risk for some typical Australian aggregates The results show that the effects of current density on AAR depend on the nature of the aggregate and the level of alkali in concrete. It appears that the 25 mA/m<sup>2</sup> current density which is the closest to the level applied in practice caused the largest increase in expansion when the alkali level was high, whereas at lower alkali content it did not contribute to the expansion. The depolarisation behaviors of selected specimens have been measured, and it appears that the presence of AAR influences the processes involved. This may have implications for the criteria normally adopted to verify the effectiveness of the operational CP systems.

Keywords: Alkali-aggregate reaction (AAR), corrosion, steel reinforcement, cathodic protection (CP), AAR gel, CP-current-density

### INTRODUCTION

Corrosion of reinforcement and alkali-aggregate reaction (AAR) are the two main chemical deterioration processes for concrete structures, each of which can lead to severe premature cracking, spalling, and finally loss of integrity. These processes are completely independent of each other and often occur separately. However, under conditions when reinforced concrete contains reactive aggregate and high alkali, and is subjected to high salt environments (such as sea water or saline ground water) both deterioration processes could take place concurrently. In other situations a reactive aggregate present in the concrete may not undergo deleterious AAR due to inadequate alkalinity in the concrete. The application of CP under this situation, to arrest the progress of corrosion, may increase the risk of AAR expansion and cracking of the concrete which would be counterproductive. Therefore, this risk needs to be assessed before the application of CP. The protection is effected by the use of an impressed current, applied to the reinforcement to counter the generation of corrosion currents.

In the process of corrosion, the anodic sites undergo an electrochemical reaction of the form  $Fe \rightarrow Fe^{2^+} + 2e^-$  which leads to the dissolution of iron at the site. The dissolved iron later precipitates as rust through a sequence of reactions, with intermediate steps such as

$$Fe^{2+} + 2H_2O \rightarrow Fe (OH)_2 + 2H^+ + 2e^-$$

At final stages, further reaction with oxygen results in rust, a mixture of iron oxide and iron oxyhydroxide. The electrons generated at the anodic site flow through the metal to the cathodic sites where they are consumed in the reaction

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

This reaction takes place under the alkaline conditions of the concrete. Under acidic conditions or at high current densities H' is reduced to H atoms which produces  $H_2$ , i.e., hydrogen gas evolution occurs.

In the cathodic-protection (CP) process, by imposing a potential difference between the anode and the cathode, a certain current density is applied to the cathode, i.e., electrons are supplied to the anode to flow to the cathode where they are consumed, so that there is no need for the anodic reaction to supply the electrons. Therefore, the anodic reaction does not proceed. However, by applying the CP current to the reinforcement the cathodic reaction continues to take place, generating hydroxyl ions. The alkali cations also move to the negatively charged steel due to the potential gradients (eg. Xu and Hooton, 1993). These reactions increase the alkalinity of the concrete, which would cause an enhanced attack on reactive aggregates (if present), and could cause deleterious AAR in the concrete. The induced AAR may not have occurred without the application of CP.

The aim of this work was to investigate the influence of CP currents on AAR susceptibility of some slowly reactive Australian aggregates, and the influence of AAR on some electrochemical properties of concrete to be protected by CP.

## LITERATURE RELATED TO THE INTERACTION OF CP AND AAR

Based on the observation of AAR in concretes subjected to electric fields, Natesaiyer and Hover (1986) hypothesised that the application of cathodic protection systems to concrete structures could promote AAR, if a reactive aggregate is present in the concrete. Preliminary results of Sergi et al. (1991) showed that CP does enhance AAR in concrete containing reactive aggregate. Detailed studies of Sergi and Page (1992) and Page et al. (1992) also provided evidence that the application of CP to a concrete containing reactive aggregate enhanced the AAR expansion around the cathode, particularly in chloride ion (CI<sup>°</sup>) contaminated concrete.

The latter two studies showed that when the cathode was potentiostatically polarised to -850 mv (SCE) or even -700 mv, the resulting current densities (which dropped sharply in the first 200 days from 300 - 400 mA/m<sup>2</sup> to 100 mA/m<sup>2</sup>) were far greater than those applied in practice in CP systems. In these cases the AAR expansion was considerably enhanced by CP, and the region affected around the cathode had a radius of 6 mm, although increased expansion was measured 25 mm either side of the cathode. When the cathode was galvanostatically polarised at 20 mA/m<sup>2</sup>, the resulting potential dropped from around -440 mv (SEC) at the time of application to about -700 mv over one year and to about -850 mv after 2 years. This current density caused only slight expansion due to AAR in specimens which would not have developed expansive AAR without it. Page et al. (1992) attributed the effect of CI<sup>°</sup> contamination on the increased AAR expansion to the fact that a substantial proportion of the anodic current density would be used in the oxidation of chloride ion to  $Cl_2$ , leaving more OH<sup>°</sup> ions in the concrete compared to the case of uncontaminated concrete. However, the present author believes that formation of chloroaluminates in the AAR-induced microcracks is also a possible mechanism of enhancing the expansion.

Page and Yu (1995) showed that at very high levels of applied current densities, in the range of  $1 - 8 \text{ A/m}^2$ , significant AAR expansion can be induced in concrete even with alkali contents below the threshold of reactivity. These authors observed a "pessimum" effect in the relationship between induced expansion and the total charge passed, and cautioned against using high current densities and long durations in testing concrete cores for AAR susceptibility in chloride extraction or desalination practices.

Ali and Rasheeduzzafar (1993) used highly alkali-enriched, reinforced mortar specimens, containing reactive glass, and current densities of 215 and 1076 mA/m<sup>2</sup>. They found that the application of these current densities caused enhanced AAR, and reductions in the compressive strength and the hardness of the mortar in the vicinity of the cathodically protected reinforcement. However, they recognised that the current densities they applied were far greater than those normally used in practice. Torii et al. (1997) applied a CP current density of 50 A/m<sup>2</sup> to reinforced concrete beams (2 by 0.2 by 0.3 m) containing a very reactive andesitic aggregate and alkali contents of 2.3, 2.6, 4.7, and 5 kg/m<sup>3</sup>. The current was applied for 3 years, and was found to have significantly increased the expansion and cracking of the beams, whose load bearing capacity decreased by 10-20% compared to the beams without the CP current.

Kuroda et al. (1996) applied cathodic current densities of 25 - 200 mA/m<sup>2</sup> to concrete prisms that contained reactive aggregate and were each reinforced with a single central rod. They measured expansion on three locations on a single face of the specimens, viz, in the centre, in the reinforcement zone between the centre and the top surface (anode was located on the top surface), and between the centre and the base of the specimens. The alkali content of the specimens varied between 0.5 to 2.5% Na<sub>2</sub>O equivalent (either as NaOH or NaCl), and some had fly ash or slag as additional ingredients. They found that expansion was larger in the upper half of the prisms (i.e. the reinforcement zone) as compared to the centre or the lower half, regardless of the application of a cathodic current density.

An interesting observation in the latter study was that expansion went through a maximum at 50 mA/m<sup>2</sup> (i.e., a pessimum effect) when the alkali content was 1.5% (NaOH), and decreased below the expansion of the control specimens when the current density was 200 mA/m<sup>2</sup>. The reason for this was attributed to the formation of a more fluid, high-alkali gel at high currents, which was suggested to be unable to create high expansive pressures in the concrete. At 50 mA/m<sup>2</sup> current density, expansion increased at all alkali levels in the absence of apozzolin or slag. When the added alkali was NaCl, maximum expansion occurred at 25 mA/m<sup>2</sup>, and it was suggested that exchange of Cl<sup>-</sup> for OH<sup>-</sup> caused an increase in the alkalinity of the pore solution, which increased the expansion of the specimens. In the presence of flyash or slag, the application of current densities lower than 100 mA/m<sup>2</sup> had little influence on the expansion of specimens with up to 1.5% Na<sub>2</sub>O equivalent, but at 100 mA/m<sup>2</sup> and alkali content of 2.5% Na<sub>2</sub>O equivalent expansion was reduced compared to the control specimens (no current). No reasons were offered for these observations.

In the study of electrochemical realkalisation of carbonated concrete, Alkadhimi and Banfill (1996) applied a current of  $1A/m^2$  of concrete, with a total charge of  $500 \pm 50$  Ah/m<sup>2</sup>. A calcined flint cristobalite aggregate was used at alkali contents of 1.8 and 2.6 kg Na<sub>2</sub>O/m<sup>3</sup>. They suggested that the electrochemical alkalisation decreased the expansion of carbonated concrete due to AAR. Their results and the appropriateness of their experimental configuration need verification.

### EXPERIMENTAL WORK

#### Materials

Four aggregates were used:

- 1. a basalt known to be non-reactive,
- 2. the same basalt with 5% of the fine aggregate replaced by opal to make it very reactive,
- 3. a reactive metagreywacke, and
- 4. a potentially reactive granite rock which shows mild petrographic signs of metamorphism.

Each aggregate was used in a concrete containing 410 kg cement/m<sup>3</sup>, at cement alkali levels of 1.1% and 1.4% Na<sub>2</sub>O equivalent, giving about 4.5 and 5.7 kg Na<sub>2</sub>O/m<sup>3</sup>, respectively. The lower alkali content was thought to be close to the threshold of alkali tolerance for the slowly reactive aggregates (under laboratory conditions).

### **Current Levels**

Four direct current densities of 0, 25, 50, and 75 mA/m<sup>2</sup> (of reinforcement) were applied with 25 mA/m<sup>2</sup> being close to the value applied in the field.

### Specimen Design

The concrete specimens measured 75 by 75 by 285 mm and contained end studs for measuring their length changes. A perforated steel plate 200 by 40 mm and 0.5 mm thick was used as the cathode. This was chosen because it was thought to produce a larger surface area but less resistance to expansion than steel bars, so that concrete expansion could take place without much restraint from the reinforcement. The anode consisted of two strips of Titanium (Ti), coated with mixed metal oxide, 200 by 20 mm and 0.5 mm thick. The cathode was located in the centre of the concrete prisms and the two anode strips cast on the two sides of the concrete prisms parallel to the cathode. Figure 1 shows the cross section of the concrete prisms and the positions of the cathode and anodes. Further details of the specimens and their connection to the power supply have been given by Shayan et al. (1998). Altogether 64 specimens were individually connected to terminals supplying appropriate current levels. Individual specimens were placed above water in small containers, lined with wet cloth and sealed to provide a humid environment, and kept at 40°C.



Fig. 1: Cross section showing the positions of the cathode and anodes in the specimen

The cathode was connected to the -ve and the joint anode to the +ve terminal of the power supply which was designed to produce constant current levels equivalent to 25, 50, and 75 mA/m<sup>2</sup> (reinforcement). These corresponded to 0.4, 0.8, and 1.2 mA current for the specimens. Some of the concrete prisms were cast with a silver/silver chloride reference electrode embedded in them in order to measure the cathode and anode potentials. Control specimens were placed under identical conditions without the application of any current. The length charge of the specimens was measured at regular intervals after disconnection from power supply and overnight recovery of the specimens in their containers at 23°C.

#### EXPANSION RESULTS

After connection to the power supply, specimens developed different cathodic potentials depending on the level of current applied. Figure 2 shows cathodic polarisation curves for

the specimens that contained reference silver/silver chloride electrodes, and were made using the non-reactive basalt aggregate at the two alkali contents. The curves show that at the higher current densities the potentials dropped significantly, and it is likely that hydrogen evolution may have taken place at these potentials, although the concrete was highly alkaline. It is not clear whether this would have an influence on the magnitude of expansion at the higher current densities in the presence of reactive aggregate.



Fig. 2: Cathodic polarisation curves for concrete prisms made with non-reactive basalt aggregate at two alkali levels

Figures 3A and 3B show expansion curves for concrete prisms containing the non-reactive basalt at the lower and higher alkali contents, respectively. The late expansion observed for these specimens is unexpected of the basalt, and it is possible that the sand component has reacted under the increased alkali levels. However, neither the alkali content nor the current level have had any significant influence on the expansion. In the case of the same basalt with 5% opal (very reactive), both the alkali level and current densities have had a significant influence on the expansion. Figure 4A shows that at the lower alkali level, increasing the current density caused increasing expansions, with the 75 mA/m<sup>2</sup> increasing the expansion by more than 50% (compared to the control specimens) at the age of 140 days although this difference decreased at later ages. However, at the higher alkali level (Figure 4B) the largest increase in expansion was caused by the 25 mA/m<sup>2</sup> current density, and smaller effects were seen for the 50 and 75 mA/m<sup>2</sup> current densities, i.e. a pessimum effect was observed, as also seen by Kuroda et al. (1996) at similar current densities and Page and Yu (1995) at much higher current densities.



Expansion curves for concrete prisms made with the <u>non-reactive basalt</u> at two alkali levels, and subjected to four levels of cathodic current alkali



Expansion curves for concrete prisms made with the basalt and 5% Opal at two alkali levels, and subjected to four levels of cathodic current densities

Relatively smaller expansions have been noted for the slowly reactive granite aggregate. Figure 5A shows that the current densities applied had some marginal effects on the expansion of the concrete prisms. The higher level of alkali has not had a significant effect on expansion at this stage (Figure 5B), but this may change at later ages. The various current densities do not seem to have affected the expansion at this stage either. Considering that the sand may have reacted in these specimens too, the remaining expansions show that the reactivity of the coarse aggregate is relatively low, and consequently it is not highly influenced by the current level.



Fig. 5A

Fig. 5B

Expansion curves for concrete prisms made with the granitic aggregate at two alkali levels, and subjected to four levels of cathodic current densities

The reactive metagreywacke aggregate has caused far more expansion that the granite. Concrete prisms made at both alkali levels have developed considerable cracking. At the lower alkali content (Figure 6A) the effect of the CP currents seems to be negative which is difficult to explain. However, at the higher alkali content (Figure 6B), the 25 mA/m<sup>2</sup> current density has clearly caused additional expansion, similar to the case of the aggregate containing 5% opal. The metagreywacke aggregate is substantially more reactive than the

granite aggregate. Data in Figure 6B are consistent with the results of Page and Yu (1995) and Kuroda et al. (1996), both showing a pessimum effect for the level of current density.



Fig. 6A



Expansion curves for concrete prisms made with the metagreywacke basalt at two alkali levels, and subjected to four levels of cathodic current densities

Figure 7 shows the value of the expansion at 18 months plotted against the current density for the four aggregates at both the lower and the higher alkali levels. These results show that at the lower alkali content, which would be closer to the field concrete, a CP current of  $25 \text{ mA/m}^2$  would not significantly increase the risk of AAR expansion.



Expansion as a function of current density



Fig. 8 (a)



Fig. 8 (c)



Fig. 8 (b)

- (a) General view of an AAR-affected concrete from a bridge structure showing extensive gel formation that covers the imprint of the steel reinforcement.
- (b) Magnified view of the imprint showing the layer of AAR gel on it.
- (c) Magnified view of the steel bar showing the AAR gel attached to it. The formation of AAR gel indicates deterioration of the steel/concrete interfacial bond.

# ELECTROCHEMICAL EFFECTS OF AAR

Shayan et al. (1998) pointed out differences in the potential decay curves of the reinforcing steel in specimens with and without AAR.

No other published literature seems to exist on the effects of AAR on the electrochemical properties of reinforced concrete. Recent observations of AAR gel coating some reinforcing bars in an AAR-affected bridge pile shows that this issue needs to be addressed. Figure 8 shows AAR gel covering the steel bar and its impression in the concrete. In the case of this bridge the piles are located in salt water, and have cracked due to AAR, and are therefore prone to corrosion. Impressed current CP could be an option, but the effects of AAR on the electrochemical behaviour of the concrete needs to be clarified.

Preliminary results obtained on some of the specimens used in this work confirm the observations made earlier [Shayan et al. (1998)] on similar specimens, regarding differences in electrochemical behaviour of reinforced concrete with and without AAR. These results will be published at a later stage.

### CONCLUSIONS

The work reported here shows that the effects of CP current density on promoting AAR in concrete depends on the nature of the aggregate, the level of alkali in the concrete and the magnitude of the current density. For the level of current density (25 mA/m<sup>2</sup>) close to that

magnitude of the current density. For the level of current density (25 mA/m<sup>2</sup>) close to that used in practice, and at low to moderate alkali levels, the CP current does not appear to contribute to AAR expansion. However, higher current levels caused increased expansions. It has also been found that the electrochemical behavior of reinforced concretes with and without AAR are different, and this could have implications for CP criteria applicable to AAR-affected structures. Further research is recommended to clarify the latter issue.

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