

Sacrificial Anodes for Cathodic Protection of Reinforcing Steel Around Patch Repairs Applied to Chloride-Contaminated Concrete

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Summary

When steel reinforcement suffers localised corrosion in chloride contaminated concrete, the most anodic regions of the metal effectively provide cathodic protection to the bars in adjacent cathodic areas. If conventional patch repair is applied to the structure, this form of adventitious cathodic protection is removed and bars which were previously behaving as cathodes in moderately contaminated areas may be transformed to anodes of cells, coupled to cathodic steel in the repaired areas. This paper demonstrates the effectiveness of combining patch repair with embedded sacrificial anodes as a means of providing continuing protection to the surrounding reinforcing bars. The sacrificial anodes designed for this purpose consist of metallic zinc in a specially formulated mortar saturated with lithium hydroxide. The high pH pore electrolyte serves to maintain the activity of the zinc, whilst the presence of lithium ions avoids the risks of alkali-silica reaction that would be incurred if other forms of alkali metal hydroxide were used.

Keywords: sacrificial anodes, concrete repairs, cathodic protection

Introduction

Dense concrete normally contains an alkaline pore liquid phase which protects embedded steel from corrosion by allowing a passive oxide film to develop on its surface under conditions where oxygen is available. This form of protection can be undermined, however, if the concrete undergoes either carbonation or chloride contamination in the vicinity of the steel. Such effects can lead to cracking and spalling of the cover concrete. In cases of chloride-induced corrosion, pitting develops at localised sites, whilst the remainder of the surface remains passivated providing a large cathodic area for oxygen reduction.

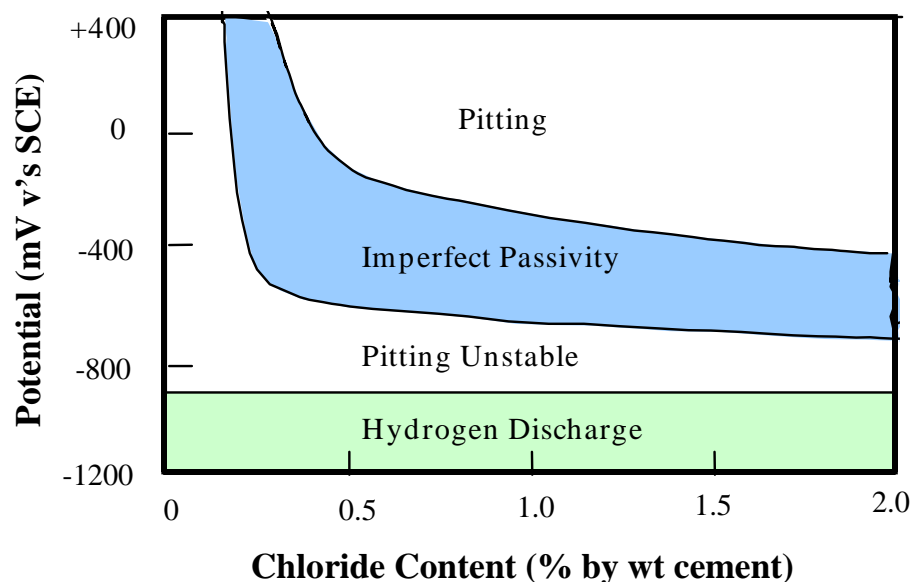


Figure 1: Approximate domains of electrochemical behaviour of steel in concretes with different levels of chloride contamination

For alkaline concrete, corrosion of steel may be expected to vary with potential and chloride content of the concrete, as illustrated by Bertolini et al [1] and summarised in Figure 1. 'Pitting' represents conditions that can lead to the initiation and propagation of pits on initially passive steel. 'Imperfect Passivity' signifies conditions that allow pre-existing pits to

propagate but do not favour the initiation of new pits on initially passive steel. 'Pitting Unstable' indicates conditions that do not allow the initiation or propagation of pits, so that pre-existing pits tend to repassivate. Finally, 'Hydrogen Discharge' represents conditions that lead to highly negative potentials and are sufficiently reducing to render the passive film thermodynamically unstable. In such cases, hydrogen is formed cathodically.

These principles underpin the application of cathodic protection (CP) to reinforcing steel in concrete. Thus to achieve adequate CP in a reinforced concrete structure in which chloride-induced corrosion has been occurring for some time, it is only necessary to polarize the steel from its condition of pitting to the domain where pitting is unstable so that repassivation can be achieved. There is no advantage to be gained in applying excessive polarization, as this would reduce the passive film as well as promoting hydrogen discharge.

Whilst most applications of CP to reinforced concrete structures have involved the use of impressed current systems with various forms of extended anode [2] there is now much interest in the use of sacrificial anodes to protect susceptible regions of the reinforcement following a conventional patch repair in chloride-contaminated concrete [3]. This paper will describe the development of an anode system specifically for such use.

Sacrificial Anode Systems in Patch Repairs

Conventionally patch repair involves the removal of chloride-contaminated concrete from around the reinforcing steel in areas where corrosion is detectable, cleaning of the exposed metal and reinstatement with fresh

alkaline concrete or mortar. The major problem with such an approach is that unless stringent measures are taken to remove all material containing significant chloride concentration from around the corroding areas, the likelihood of corrosion reappearing and cracking the concrete adjacent to the repairs is high [4]. This is because replacement of the most intensely anodic regions of the reinforcement with passive steel in the repaired zones effectively removes the adventitious form of sacrificial anode CP that was formerly being applied to the steel in the neighbouring regions (Figure 2a). Hence the potential of the metal in these less severely contaminated areas can rise to a value at which pitting is liable to be initiated (Figure 2b).

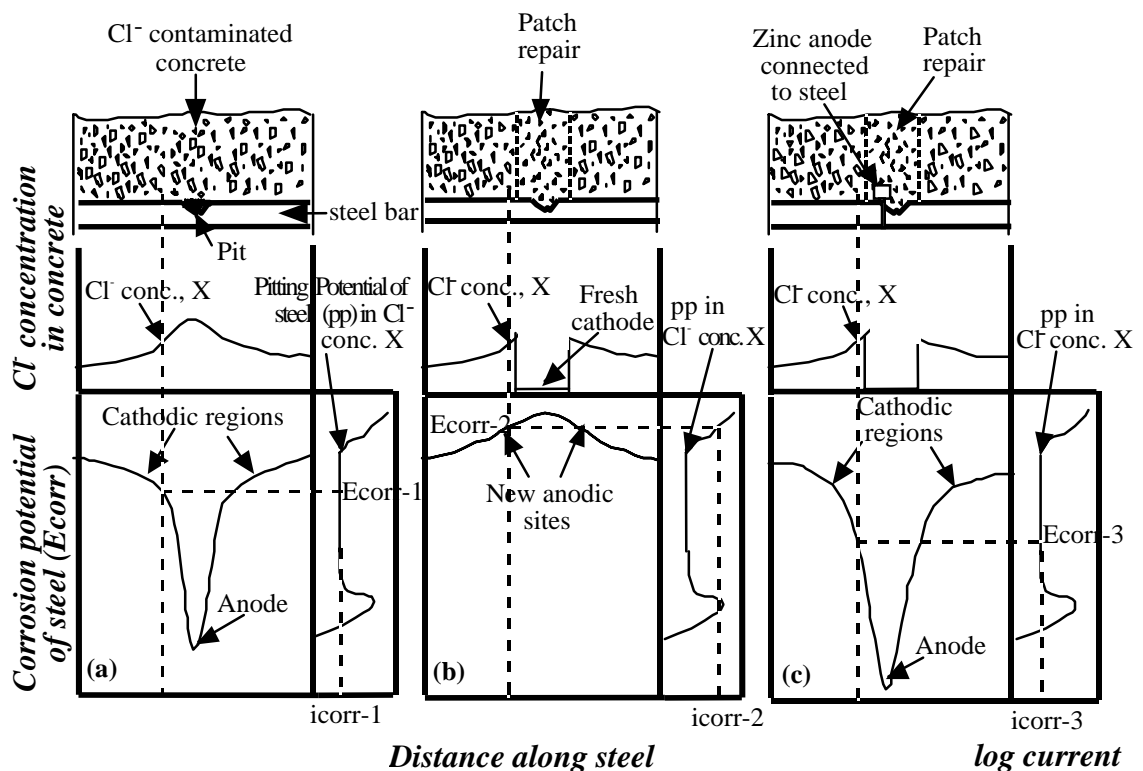


Figure 2: (a) Localised corrosion of steel in chloride-contaminated concrete, (b) Incipient anode formation on steel in 'patch-repaired concrete', (c) Protection of steel in 'patch-repair' from zinc sacrificial anode

To avoid triggering this problem of corrosion at incipient pits around the repair zones, it is desirable to reinstate some form of intentional 'cathodic prevention' and this can be accomplished with sacrificial anodes of an

appropriate design, which are embedded near the periphery of the repair patches (Figure 2c). A form of sacrificial anode, which has been found to be successful under laboratory conditions, consists of zinc encased in a high alkalinity mortar. The ability of zinc to maintain an appropriate level of current when coupled to steel reinforcement was shown to be directly related to the pH of the surrounding mortar (Figure 3) and the use of mortars saturated with LiOH ($\text{pH} > 14.5$) provides a suitable environment (Figure 4). The reservoir of excess LiOH maintains a constantly high pH value in the pore solution, which promotes and sustains the anodic activity of the zinc, whilst the presence of lithium ions is intended to inhibit problems of alkali silica reaction in the surrounding concrete if susceptible aggregates happen to be present [2].

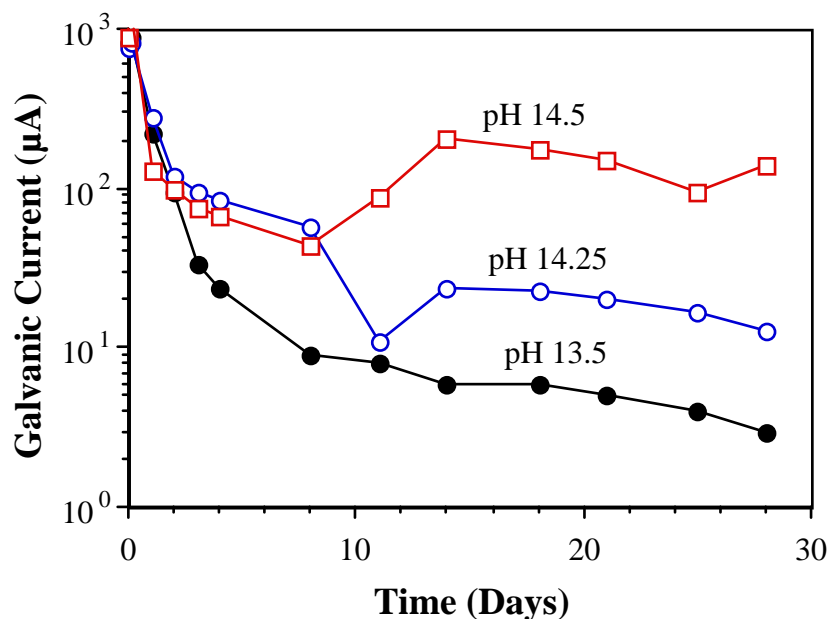


Figure 3: Galvanic current between zinc anodes embedded in mortars of controlled pore-solution pH and steel cathodes embedded in mortars containing 1% chloride by weight of cement

Experimental Evaluation

To evaluate the performance of sacrificial anodes of the type illustrated in Figure 4, a number of reinforced concrete slabs, 1000 mm x 500 mm x 100 mm, were made with two different amounts of sodium chloride (0.8% and 4% chloride by weight of cement) cast into them at specific locations, as shown in Figure 5.

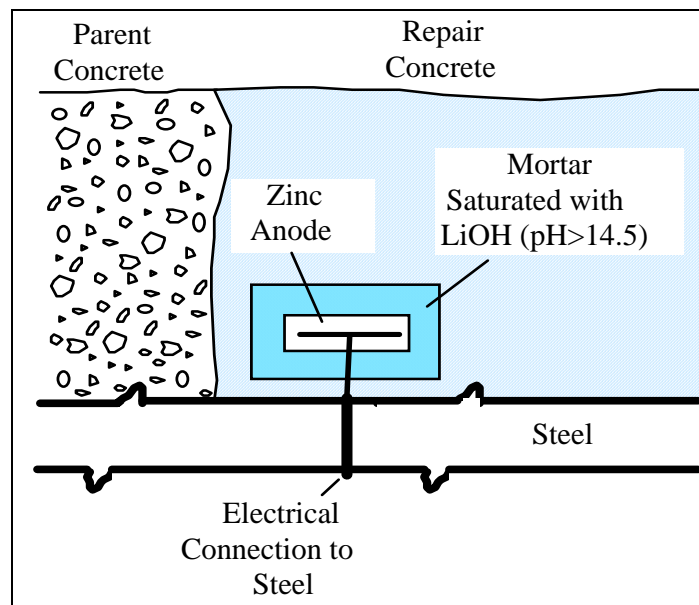


Figure 4: Zinc sacrificial anode contained in a specially formulated mortar and connected to the steel reinforcement in a patch repair

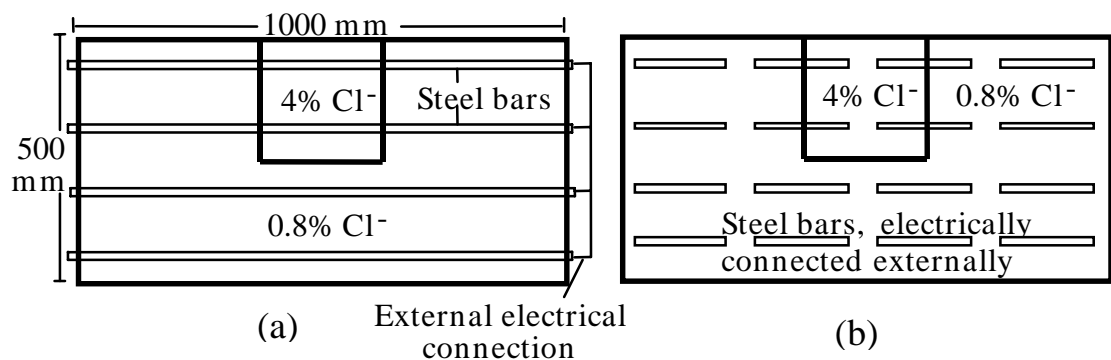


Figure 5: Concrete slabs with chloride concentrations and arrangement of steel reinforcing bars as shown

Four steel bars were embedded at equal intervals along the whole length of each slab and electrically connected externally (Figure 5a). Some had each of the four bars replaced by four shorter lengths of bar, giving a total of

sixteen individual bars as shown in Figure 5b. The middle section of the top two bars (or lines of bars) lay in the zone of high chloride concentration. It was this area that showed considerable cracking of the concrete caused by reinforcement corrosion after exposure of the slabs either outdoors or in a constant 80% RH environment at room temperature for a period of 350 days. The damaged concrete was removed exposing the corroded reinforcement and, after cleaning of the bars, fresh chloride-free repair concrete was cast, restoring the original shape of each slab. In some slabs, a single disc of zinc metal weighing approximately 80g embedded in a specially formulated mortar containing an excess of LiOH over the amount required to saturate the mix water was buried and electrically connected to the steel reinforcement externally. The slabs were then repositioned either outdoors or in the constant RH environment in the laboratory. Potential mapping surveys were carried out at appropriate times and the current passing between the zinc anode and the steel reinforcement was monitored regularly.

Figure 6 shows a sequence of potential maps for two slabs exposed to the constant 80% RH environment. Prior to repair, both showed anodic regions within the areas of high chloride concentration, signifying corrosion of the steel (Figs 6a & 6c). One month after repair, Slab-B, which contained the zinc anode, maintained the most anodic region within the repaired patch (Fig. 6d), whilst Slab-A, without a zinc anode, developed a new cathodic region within this freshly repaired area. Consequently, new anodic sites, represented by the more negative potentials, appeared outside the patch after only two months (Fig. 6b). After 18 months, although the overall potentials became less negative, the anodic region remained within the repaired area of Slab-B (Fig. 6e). Disconnection of the anode for 24 hours, confirmed that the steel had been cathodically polarised by the zinc anode

as the potentials of the steel showed substantial depolarisation shifts (Fig. 6f).

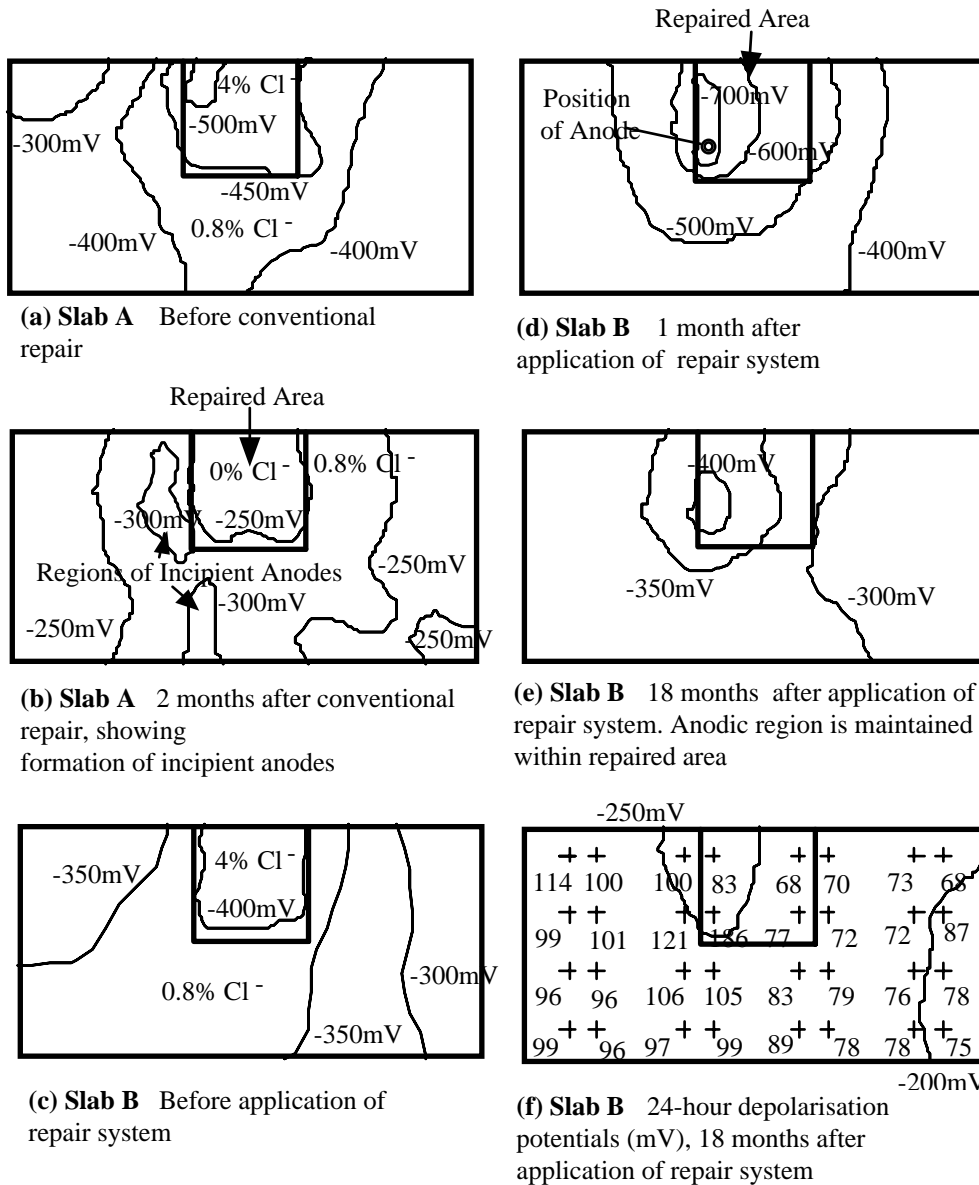


Figure 6: Slabs A and B before and after repair

The current, measured between the anode and steel reinforcement of the Slab-B for about 2 years remained above $60 \mu\text{A}$ when the concrete was exposed for extended periods to an external RH, maintained at 80% or higher (Fig. 7). This represents a current density of about 1 mA/m^2 of steel, a level believed to be adequate for cathodic prevention [1].

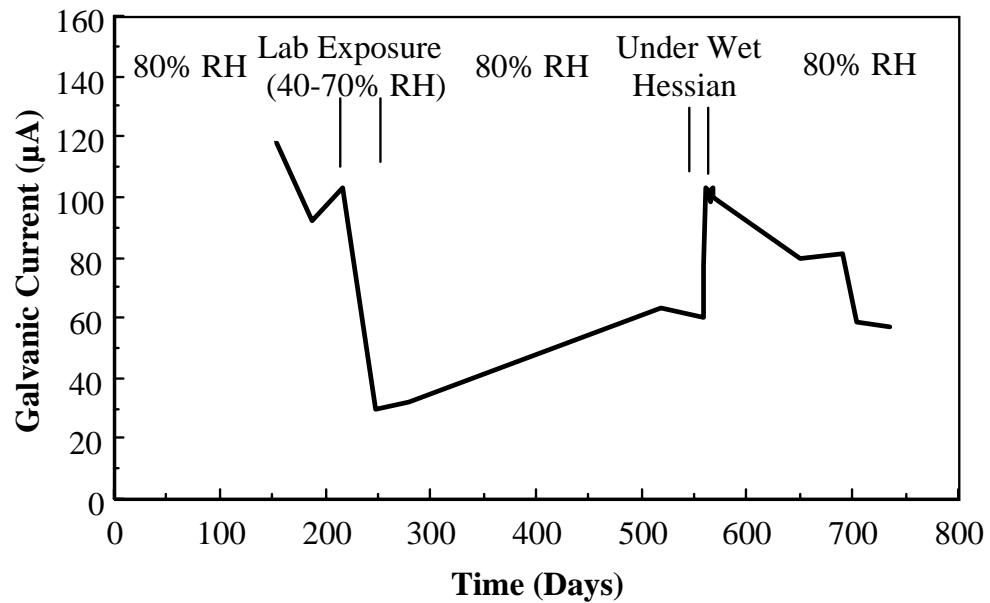


Figure 7: Variation of galvanic current between the buried sacrificial zinc anode and the steel reinforcement of Slab-B

As a result of cathodic polarization of the steel in concrete, there is a tendency for the material in the vicinity of the steel cathode to become enriched with respect to OH^- , Li^+ , Na^+ and K^+ whilst being depleted of Cl^- and O_2 . Correspondingly, at the anode the surrounding material becomes progressively acidified and enriched with Cl^- . The enhancement of the OH^- concentration and reduction of the Cl^- concentration near the steel surface are both beneficial in reducing the risk of corrosion. The movement of chloride was illustrated in mortar composite specimens half of which contained 2% Cl^- by weight of cement and a steel electrode whilst the other half contained excess LiOH and a zinc electrode. On coupling the electrodes, a current flowed between them, gradually diminishing from an early level of $1.5 \mu\text{A}$ over a period of 50 days. Determination of the chloride concentration profile at termination by a dry profiling technique and analysis showed that the normal chloride migration by diffusion observed in the control samples was enhanced by polarization (Fig. 8).

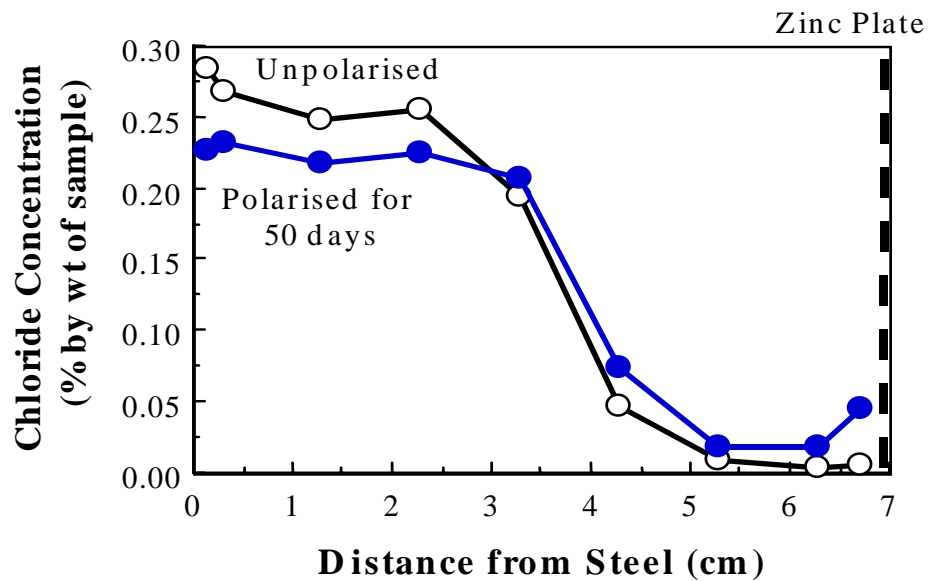


Figure 8 Average chloride concentration profiles between the zinc and steel electrodes in cementitious composite mortars

Field trials involving the use of sacrificial anodes of the type shown in Figure 4 in patch repairs applied to reinforced concrete structures are now in progress and early results have been encouraging.

Conclusions

Zinc sacrificial anodes encased in a specially formulated mortar containing a pore electrolyte saturated with excess LiOH were shown experimentally to provide adequate cathodic prevention of the steel in repaired areas of concrete which were originally contaminated with high levels of chloride. Polarisation of the reinforcement was maintained for a period of at least two years.

The current densities obtained were sufficient to cause significant migration of chlorides into the repair from the surrounding material.

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