

Surprisingly Effective Cathodic Protection

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ABSTRACT

This work examines the effect of current distribution on the basis for cathodic protection of steel in concrete. It is noted that cathodic protection at integrated current densities that are small compared to the corrosion rate will induce changes in the local environment at the steel that promote steel passivity in chloride contaminated concrete. In conditions characterised by weakly polarised cathodic reaction kinetics, cathodic protection of steel in concrete ultimately induces anodic polarisation on actively corroding steel. This renders low current densities surprisingly effective in achieving protection of actively corroding steel. The instantaneous protective effects of cathodic polarisation are negligible. The protection current tends to flow to the more positive cathodes in the active-passive macro-cells that exist on steel in chloride contaminated concrete, even when geometry and resistivity might favour current flowing to the anodes. Such currents reduce the macro-cell activity that sustains the concentration gradients in the concrete environment necessary for pit growth.

Keywords: Concrete, Cathodic Protection, Current Distribution, Corrosion Cell, Chloride, Passivity, Reinforcing Steel

INTRODUCTION

Cathodic protection is a widely accepted repair technique for concrete structures. Its development has largely been empirical, with the success of early trials on experimental systems resulting in its widespread acceptance [1]. The design of these systems tends to be based on previous experience. This work reviews the theoretical basis for reinforced concrete cathodic protection and examines the effects of current distribution in the presence of macro-cell corrosion activity on the achievement of protection.

BASIS FOR PROTECTION

The conventional basis for cathodic protection relies on inducing a negative steel potential shift [2]. This reduces the tendency for iron to dissolve as positive ions. It is achieved by polarising the cathodic reaction kinetics, hence the name cathodic protection [1]. However the conventional understanding of cathodic protection needs to be extended to include the significant polarisation of the anodic reaction kinetics on the protected steel surface [3,4]. A cathodic current also results in a less aggressive environment at the cathode that promotes steel passivity [5,6]. As a result, a significant reduction in the open circuit corrosion rate of the steel occurs.

The effect of inducing a reduction in the open circuit corrosion rate is particularly important when the cathodic reaction kinetics are weakly polarised as is often the case for

steel in atmospherically exposed concrete. It has been noted that conventional cathodic protection in conditions characterised by weakly polarised cathodic reaction kinetics may be rendered uneconomic by a very high protection current requirement [7].

The effects of anodic polarisation on the protected steel are illustrated in Figs.1 to 5. The data points in Fig.1 give a typical relationship between the corrosion potential and corrosion rate in reinforced concrete [8]. An increase in the steel corrosion rate is often accompanied by a more negative corrosion potential. This potential-corrosion rate relationship is observed when the cathodic reaction occurs relatively easily (the cathodic reaction kinetics are weakly polarised). An increase in corrosion rate is caused by depolarisation of the anodic reaction kinetics (the dissolution of iron occurs more easily) [4]. The Evans diagram illustration of this is included in Fig.1 (red and blue lines).

The visual effect of a range of cathodic protection current densities applied to reinforced concrete cylinders containing 2% chloride by weight of cement exposed to simulated sea water for half an hour twice a day, and to dry circulating laboratory air at other times is given in Fig.2 [9]. The protection current was applied only while the specimens were immersed in seawater. The current densities reported in Fig.2 are integrated current densities.

At integrated protection current densities below 5 mA/m² of steel, corrosion induced cracking occurred although the time to cracking increased with the application of a protection current. At higher current densities, corrosion induced cracking was prevented. It was also observed that the applied protection current densities preventing cracking were sometimes very low compared to the initial corrosion rates determined on these specimens. This suggests that protection may be achieved with a cathodic current that is

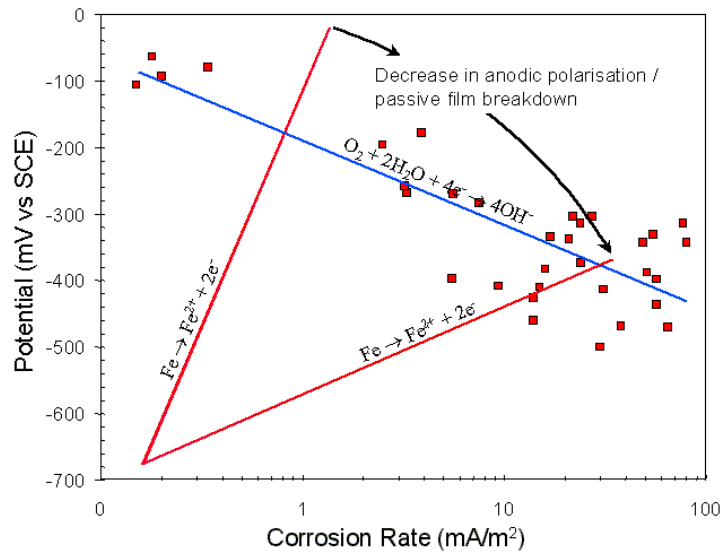


Fig. 1 Corrosion potential- corrosion rate relationship and its Evans diagram explanation.

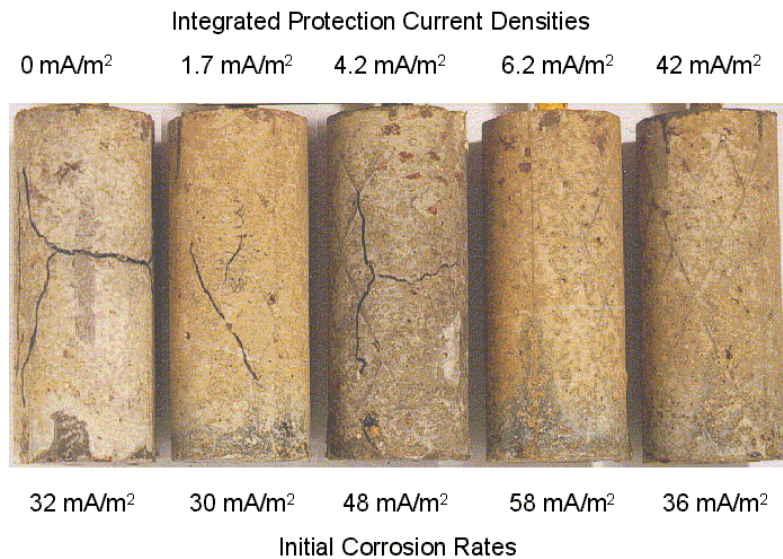


Fig. 2 Effect of the protection current density on the condition of 100mm diameter reinforced concrete cylinders containing 2% chloride.

small compared to the corrosion rate.

The open circuit potentials of the steel in the specimens in Fig.2, determined 8 hours after the current was last applied, are given in Fig.3. In cases where corrosion induced cracking was prevented, a positive shift of more than 200 mV occurred. When corrosion was not arrested, the potentials remained unchanged or fell to even more negative values [10].

A positive shift in the open circuit steel potential has been reported in many practical reinforced concrete cathodic protection installations at the locations where the most negative potentials were initially determined [11]. The initial corrosion potentials as well as the open circuit potentials determined after 12 months of cathodic protection by interrupting the current for 24 hours on the piers of a bridge are given in Fig.4. This shows that the most negative potentials associated with the highest corrosion risk have moved by at least 150 mV in the positive direction [12]. It may be noted that relatively low current densities between 3 and 12 mA/m² were applied in this case.

The explanation for a 200 mV positive shift (cf. Fig.3) in the open circuit corrosion potential for a steel that is initially corroding at 30 mA/m² is illustrated in Fig.5. Such a positive shift in the open-circuit potential would result from a current induced change in the environment at the cathode. In this case an open-circuit corrosion rate of 30 mA/m² would be reduced to less than 1 mA/m² [4].

Included in Fig.5 is the effect of applying a relatively high current density (40 mA/m²) on the rate of steel dissolution when the steel is initially corroding at 30 mA/m² and the anodic reaction kinetics remain unchanged. The rate of steel dissolution reduces from 30 to 15 mA/m² as the result of the negative potential shift induced. This is a relatively small reduction and implies that the effects of a negative potential shift are not that significant.

It may also be noted that it would be practically difficult to

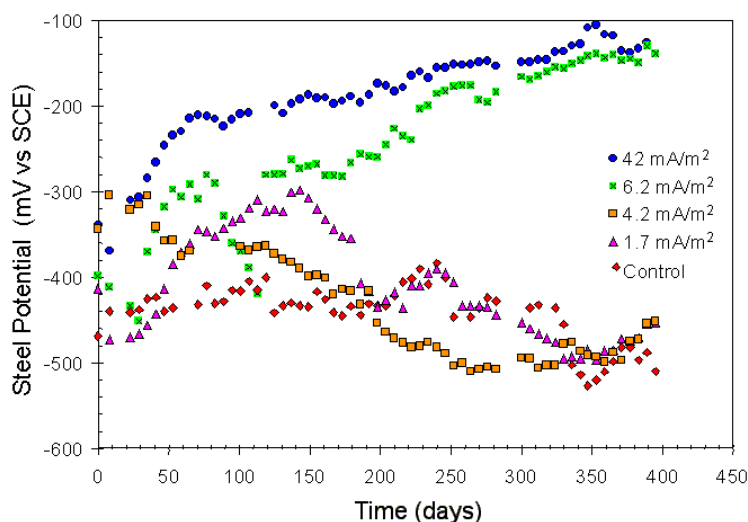


Fig. 3 Effect of integrated protection current density on the corrosion potential of the steel (cf. Fig.2) determined 8 hours after interrupting the current.

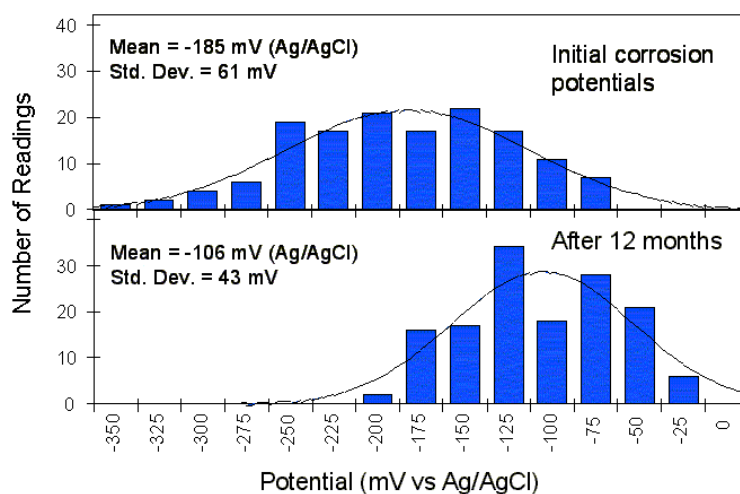


Fig. 4 Analysis of open circuit potential data determined 24 hours after interruptin the protection current applied to bridge piers.

sustain a protection current density of 40 mA/m². Reinforced concrete cathodic protection design current densities up to 20mA/m² are used and the applied current densities will be lower [13].

CURRENT DISTRIBUTION

Background

Another proposed explanation for the effectiveness of practical cathodic protection of steel in concrete is that the corrosion of reinforcing steel is a localised phenomenon and that the protection current is concentrated at the actively corroding anodes. This hypothesis might support the more conventional basis for cathodic protection and is examined in this section.

Theoretical and empirical studies have been undertaken to investigate the distribution of current in reinforced concrete cathodic protection systems [14,15]. Non-linear cathodic boundary conditions exhibiting activation controlled anodic and cathodic kinetics at small current densities and mass transfer controlled cathodic kinetics at large current densities relate the corrosion rate of the cathode to the corrosion potential which affects current distribution when the steel is not corroding at a uniform rate. Changes in the open circuit corrosion rate with time resulting from the electric field driving a variety of beneficial changes have also been modelled [16]. Some models are now freely available as public domain software [17]. .

Cathodic Kinetics and Geometry

The boundary conditions at the cathode are mainly determined by the cathodic micro-cell behaviour. The cathodic polarisation curves measured on concrete specimens containing a range of chloride contents to produce steel bars corroding at rate between 1 and 16 mA/m², are given in Fig.6. After a sufficient negative potential shift has been achieved (the local cathodic reaction has been increased and anodic

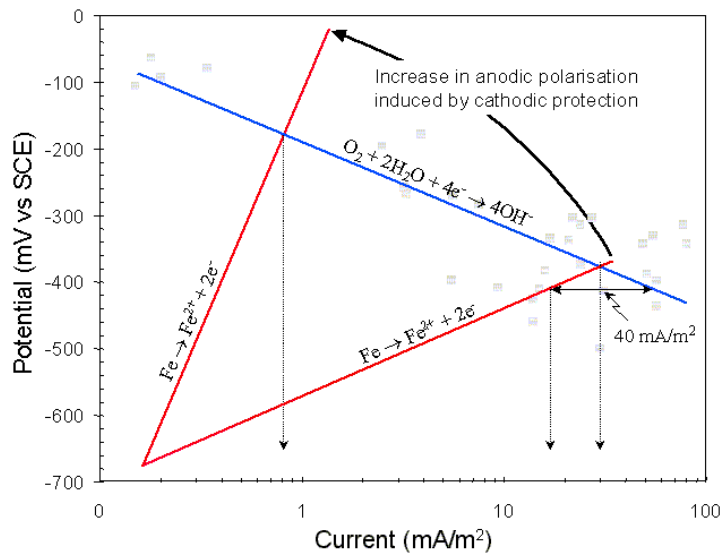


Fig. 5 Evans diagram interpretation of the positive shift in open circuit potentials observed on cathodic protection systems.

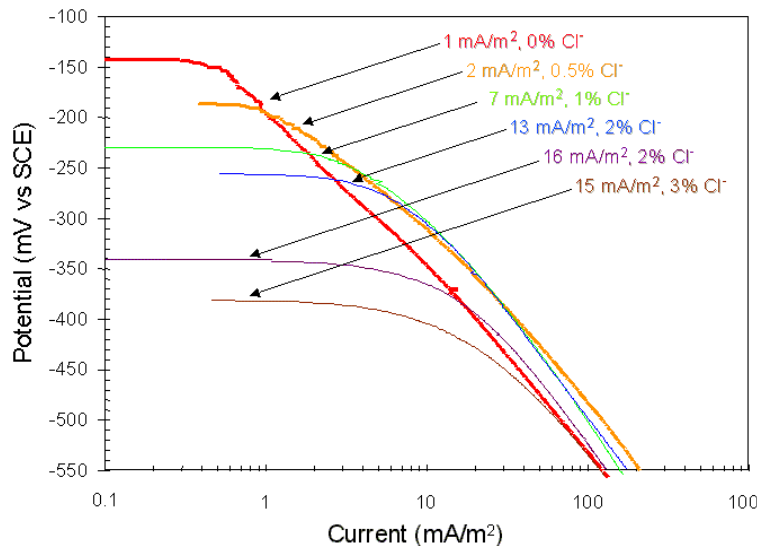


Fig. 6 Cathodic polarisation curves determined on steel in concrete exhibiting a range of initial corrosion rates resulting from variations in chloride content.

reaction reduced such that the cathodic reaction kinetics dominate the behaviour observed), the rate of cathodic reduction appeared to be independent of the initial corrosion rate. This suggests that the cathodic reaction kinetics, described mainly by the cathodic Tafel slope and exchange current density for oxygen reduction, are independent of corrosion rate.

Any dependency of the cathodic reaction kinetics on the presence of a passive film was masked by the factors that also render corrosion potential an imperfect indicator of corrosion rate. This suggests that changes in the cathodic reaction kinetics on passive and active steel would not significantly favour current distribution to active areas over passive areas.

The effect of increasing the applied cathodic current density on the current distribution to bars corroding at ostensibly the same rate, but embedded at different depths from a surface applied anode was measured for combinations of bars exposed to the same chloride contaminated concrete. The concrete specimens consisted of prisms with a 100 mm square section containing parallel 10mm diameter bars spaced at 110mm intervals. The specimen length depended on the number of bars in the prism. An anode was installed on the end of the prism with the first bar being 55mm from the anode.

Fig.7 gives an example of the specimen layout and the effect of the applied current density on the current distribution between two passive bars. At low current densities ($< 5 \text{ mA/m}^2$) very uniform current distribution was achieved. As the applied current increased, significantly more current started to flow to the bar closest to the anode. It received 55% and 59% of the total current at 10 and 25 mA/m^2 respectively.

Fig.8 gives the same effect on specimens containing two active bars. In this particular case the current distribution was very poor initially, probably as the result of some macro-cell activity. It improved as the applied current was increased

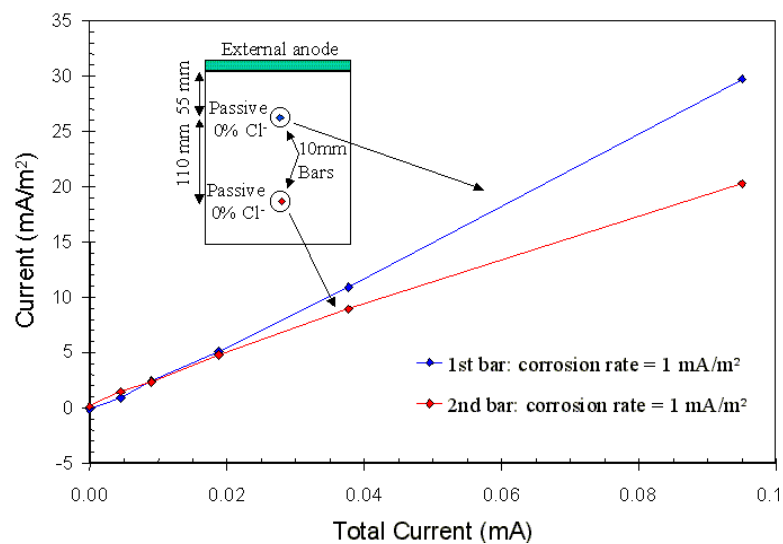


Fig. 7 Effect of the applied current on the current distribution to passive bars at different depths.

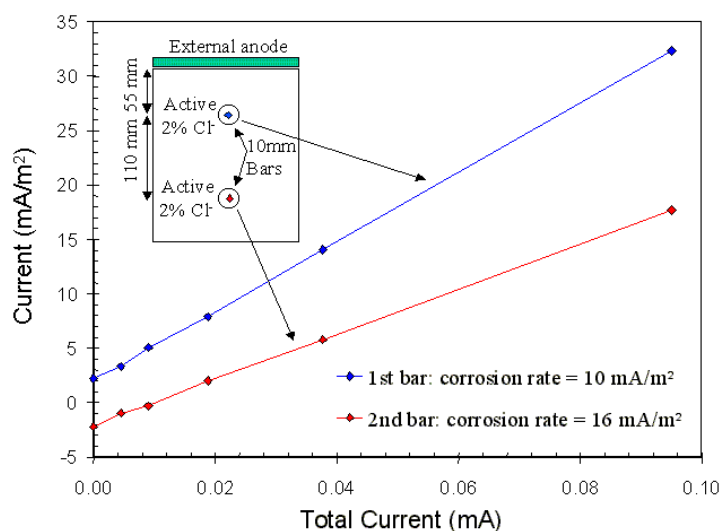


Fig. 8 Effect of the applied current on the current distribution to active bars at different depths.

with the bar closest to the anode receiving 71% and 65% of the total current at 10 and 25 mA/m² respectively. It was generally noted that at low current densities the distribution of current was very dependent on the initial corrosion rate with very good current distribution being achieved on passive steel. At high current densities the distribution of current was dominated by environment resistivity and geometry irrespective of whether the steel was passive or not.

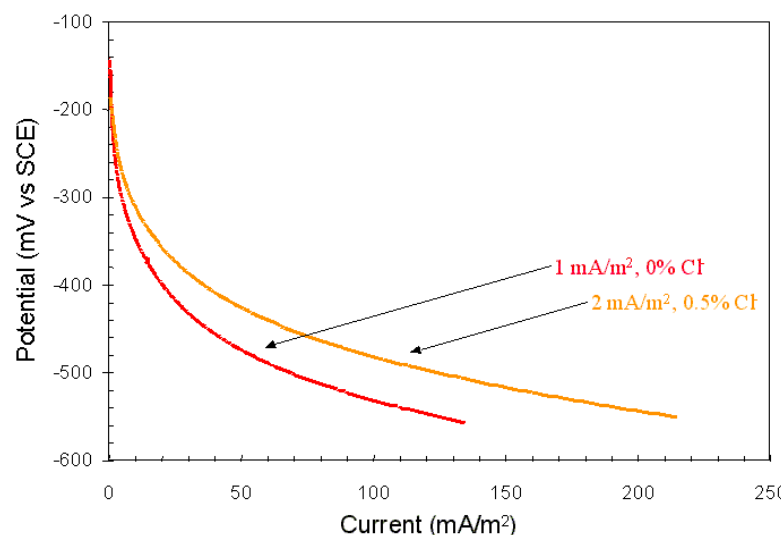


Fig. 9 Illustration of the effects of the rate of cathodic reduction (current) on the resistance to cathodic reduction (slope of potential vs. current) (cf. Fig.6).

The explanation for this comes from the effect of the cathodic reaction kinetics on current distribution. In Fig.9 the cathodic polarisation behaviour obtained on the “near passive” steel in Fig.6 has been plotted on a linear (as opposed to a log) scale. The slope of the curve (change in potential over change in current) gives an indication of the resistance to current flow across the interface presented by the cathodic reduction reaction. It is evident that, at low rates of cathodic reduction associated with passive steel and low current densities, the steel-concrete interface exhibits a high resistance to current flow. This has a beneficial effect on current distribution.

As the rate of cathodic reduction increases an apparent reduction in the resistance at the interface occurs. The resistivity of the environment and the geometry of the system then dominate current distribution. A high rate of cathodic reduction may be induced by either a high corrosion rate or a large applied current. Thus, poor current distribution may occur even when all the steel is passive if a large current density is applied, although a small current density will always give rise to a large potential shift on passive steel.

Macro-Cell Corrosion Activity

The distribution of current in reinforced concrete cathodic protection systems is complicated by the existence of active-passive macro-corrosion cells on the steel. Not only do different areas of the steel exhibit different corrosion rates but they also have different corrosion potentials (cf. Fig.1). The polarization curves measured on active and passive steel (cf. Fig.6) suggest that the current required to shift the potential of passive steel to that of active steel would be of the same order as the active steel corrosion rate.

The effect of the applied current density on the distribution of current in an active-passive galvanic couple is given in Fig.10. It is evident that, although geometry and resistivity favour current flowing to the corroding steel, the only effect of the applied current is to overcome the galvanic effects of the active-passive couple at low current densities. It was generally observed that, when a cathodic protection current density below the open circuit corrosion rate of the active steel in an active - passive galvanic couple is applied, the current flows to the more positive passive sites [15].

This contradicts the idea that current will flow to the active areas of the steel. The effect of the protection current is to reduce the galvanic current in the active-passive couple.

This supports a pH gradient in the local environment necessary to sustain localised corrosion activity. The oxides that form the passive film on steel in concrete are thermodynamically stable in the high pH environment in concrete, even when chloride ions are present. The removal of the galvanic current arising from an active-passive couple allows the pH at the active anode to rise to that in the adjacent environment.

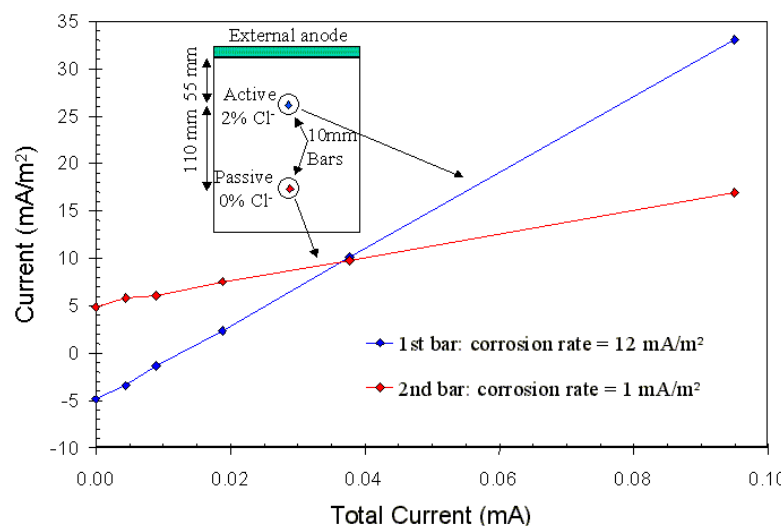


Fig. 10 Effect of the applied current on the current distribution to bars at different depths in an active-passive galvanic couple.

As the applied current density increases above the open circuit corrosion rate of the active sites and the protection potential falls below the open circuit active corrosion potential, the distribution of current is increasingly dominated by the resistivity and geometry of the environment and the flow of current to actively corroding sites may be favoured by a lower local environment resistivity. However the high localised corrosion rates of active steel (typically up to 100 mA/m^2 or $100 \text{ } \mu\text{m/yr}$) may render a favourable distribution of current difficult to achieve. The absence of evidence suggesting that current will preferentially flow to actively corroding sites at low applied current densities supports the hypothesis that the negative potential shift achieved in cathodic protection of steel in concrete has a negligible effect in arresting active corrosion.

The success of the widespread use of low current densities in the cathodic protection of steel in concrete results from the current induced improvements in the environment at the cathode. This includes the removal of chloride and the continuous production of hydroxyl ions at the steel as a result of the cathodic reduction reaction. A source of hydroxyl ions will sustain a high pH environment at the steel and prevent the local reduction in pH that is necessary to sustain pit growth [4]. The experimental data given above (cf. Fig.2) suggests that low current densities are surprisingly effective at arresting corrosion of steel in reinforced concrete.

CONCLUSIONS

Cathodic protection at integrated current densities that are small compared to the corrosion rate will induce changes in the local environment at the steel that promote steel passivity in chloride contaminated concrete.

A basis for the cathodic protection of steel in concrete in conditions characterised by weakly polarised cathodic reaction kinetics is that it polarises the anodic reaction kinetics on actively corroding steel.

The instantaneous protective effects of a negative steel potential shift induced by a relatively small practical current density may be neglected in concrete where oxygen has easy access to the steel. In other words, the effects of cathodic polarisation induced by cathodic protection of steel in atmospherically exposed concrete are negligible.

The protection current tends to flow to the more positive cathodes in the active-passive macro-cells that exist on steel in chloride contaminated concrete, even when geometry and resistivity might favour current flowing to the anodes. Low protection current densities reduce the corrosion cell activity that sustains the concentration gradient in the concrete environment necessary for pit growth.

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