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Investigation of the residual protection of steel following application of protective current

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HIGHLIGHTS

- Residual passivation was observed on both the laboratory and site trial specimens.
- The duration of the continued protection increased with duration and total charge passed.
- A longer protection period was observed for lower current densities at same charge.
- A second application resulted in an increase in the duration of protection.

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ABSTRACT

Recent studies have shown that when the operation of steel reinforced concrete impressed current cathodic protection systems is halted the steel can remain passive for a period of time. This paper reports a systematic study using both laboratory specimens and a small scale site trial to investigate the factors influencing the occurrence and duration of residual protection using charge densities of 20, 60, 180 and 540 mA/m^2. Both the laboratory and site specimens demonstrated short term residual protection. The results indicated that the residual protection was dependant on both the duration and charge passed, with longer periods of protection observed on site following a second application of current.

1. Introduction

The majority of the infrastructure built today is made from steel reinforced concrete. As a result of this widespread use, the corrosion of steel reinforcement costs billions of dollars annually in repair and maintenance. It was estimated in 2010 that this corresponds to 3% of the world gross domestic product ($73.3 trillion) [1]. One of the most widely adopted repair techniques is impressed current cathodic protection (ICCP) which has been shown to be an effective method of halting corrosion. ICCP has become widely accepted and is one of the most used techniques for the rehabilitation of reinforced concrete structures suffering from chloride-induced corrosion. The use of ICCP systems is now covered in national and international standards worldwide [8,21,3].

ICCP operates by negatively polarising the steel's potential in order to shift the steel/concrete potential into a region where a) the initiation of corrosion, or b) if corrosion has already started, the continuation/propagation of corrosion; is so far suppressed, that a corrosion failure is unlikely during the lifetime of the structure, ISO 12696:2016 [15]. Research has shown that the application of ICCP also induces secondary changes in the local environment at the steel/concrete interface. This is due to the removal of chloride ions from the vicinity of the steel coupled with the production of hydroxyl ions at the steel surface, resulting in the restoration of the steel passivity [6,9,13,16]. Current standards state that initial polarisation of the steel can employ a current of up to 20 mA/m^2. In the early years of the technology the current was maintained over the life of the ICCP system, however it is now general practice to reduce the current to the minimum level required to maintain protection as per the relevant standard [24,26]. In addition to saving energy, lowering the applied current extends the lifetime of the ICCP system and reduces the likelihood of acid attack at the anode [25].

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Past studies on structures with ICCP systems have reported evidence of continued passivation and protection (based upon a number of factors including, steel potentials, corrosion rates and continued increase in potentials to more positive values [23,27,7,9,14] even after the current has been halted. This ongoing protection is known as residual protection. Residual protection of structures has been observed to last for several years however it is not observed in all structures [28,22,5]. While studies have confirmed the presence of continued protection, to date there has been no systematic study on which factors are critical to it. Potential factors include applied charge density, duration of current application, total amount of charge passed, concrete chloride content and structure environmental conditions. The understanding of how these factors influence continued protection could contribute to the improved operation of ICCP systems over the long term. These benefits include potentially extending the lifetime of existing systems by enabling them to be de-activated (or pulsed) through their operational life. Furthermore, studying the factors determining the length of residual protection can also enable inspection, maintenance and repair actions of structures to be scheduled with confidence that the ICCP can be deactivated without compromising the protection.

This paper reports on a study undertaken to investigate the post application effects of ICCP. The trial employed a range of current densities (20, 60, 180 and 540 mA/m^2 based on steel surface area) for two time periods (one and three months). The research included both laboratory trials and the installation of a small scale trial ICCP system on a port structure displaying significant levels of distress. The parameters monitored included resistivity, temperature, humidity, steel potential and corrosion rate.

2. Methodology

The laboratory specimens were based on a previous pilot study to determine an appropriate configuration for the monitoring sensors [5]. The test regime included seven specimens in the laboratory trial, together with two test panels on site. The laboratory specimens consisted of 100% ordinary Portland (CEM I) cement mix with a nominal cube strength of 40 MPa (achieved 42.7 MPa at 28 days). This was chosen to simulate the likely mix used in the construction of the seawall location utilised for the site trial. However, only seven mm aggregate is used to accommodate the resistivity sensors which had a spacing requirement of 10 mm. Use of larger sized aggregates may have caused unwanted voids between the sensors. Salt was added to the mix in order to accelerate the corrosion process. To achieve this, 3% NaCl by weight of cement was added to the mix. The mix design is given Table 1.

The specimens dimensions were 300 × 150 × 100 mm with a ribbed mild steel bar, diameter 16 mm and length of 250 mm, Fig. 1, embedded with 40 mm cover of concrete cover. The anode was an activated titanium mesh ribbon anode (De Nora Type 1 – current rating of 5.5 mA/m at 110 mA/m^2), which was embedded parallel to the rebar with 20 mm cover both to the bar and from the surface. Potential monitoring was undertaken with an embedded Ag/AgCl0.5 M KCl electrode (Castle type LD15, referred to as Ag/AgCl), temperature with a welded-tip thermocouple, relative humidity (RH) with a humidity sensor (Honeywell HIH4000-01) and resistivity using three pairs of embedded resistivity sensors, P1, P2 and P3 connected to a LCR meter (Isotech LCR819) [5,20]. The resistivity sensors were installed 10 mm apart, with sensor P1 adjacent to the rebar, P2 and P3 positioned between the bar and the concrete surface. The sensors are installed to provide data on changes in resistivity at the steel/concrete interface arising from the changes in concentration of ions in this region. The sensor spacing is minimised to better detect any variations in resistivity in the concrete in the region around the rebar. The reference electrode and RH probe at 50 mm from the rebar surface, Fig. 1. The specimens were subjected to a wet/dry cycle to initiate corrosion. Wetting took place by 30 min of spraying with tap water every 12 h using a pump connected to a digital timer. The RH within the cabinet was approximately 65% during the drying period. The conditioning was continued for three and a half months prior to the application of cathodic protection.

Table 1
Mix Design.

Constituent	Quantity (kg/m^3)
Cement	420
Water	210
Fine Aggregate	625
Coarse Aggregate (7 mm)	1250
NaCl	12.6

The applied charge densities were 20, 60, 180 and 540 mA/m^2 of steel surface area and were applied for durations of one and three months, Table 2.

A current density of 20 mA/m^2 was selected as this corresponds to the maximum design current density allowed. Previous research has indicated current densities up to 200 mA/m^2 can be applied without adverse effects on the steel/concrete interface [11]. In order to compare and study the relationship between current density and total charge, 60 and 180 mA/m^2 were selected. This would provide the same amount charge passed for 20 mA/m^2 for three months compared with 60 mA/m^2 for one month, with the same ratio for the 180 mA/m^2 specimens. Finally, specimens were also tested at 540 mA/m^2, maintaining the 3:1 ratio between time and current enabling a higher total charge passed to be assessed for both residual protection and the viability as a possible accelerated technique to enable the predicted performance in structures where ICCP had been applied for long periods.

The degree of corrosion was monitored both by the steel potential and corrosion rate (measured using Linear Polarisation Resistance (LPR) [10,19]. LPR measurements were taken using a three electrode system under potentiostatic control, with a polarisation of ± 10 mV for a 30 s equilibrium period, using a Stern-Geary constant, B, of 26 mV and a 300 Hz AC signal to compensate for the IR drop [17,18]. The protective current was applied by connecting the rebar to the negative terminal of the direct current (DC) power source and the anode mesh to the positive terminal.

The site trial took place on a 40 year old seawall located at a Port on the southern coast of Australia. The structure is exposed to severe winter storms with regular splash and spray with sea water. The wall is showing significant signs of deterioration with rust staining, cracking, delamination and spalling present.

Steel potential measurements, taken using a Cu/$CuSO_4$ electrode on a number of panels, including those in this trial, all showed potentials in excess of −350 mV (vs Cu/$CuSO_4$) indicating high probability of corrosion, in accordance with Van der Veer criteria [4]. Given these details it is assumed that corrosion is well established in the structure and has been initiated by exposure to chloride from the marine environment.

An ICCP trial was installed in two panels identified as displaying active corrosion, based on the steel potentials, but with no cracks or spalls present. Ribbon anodes were installed into two slots running the length of the panel, with two Ag/AgCl reference electrodes installed at the left and right edges for monitoring, Fig. 2 and Fig. 3. Reverence electrodes A & B are in panel 1 and reference electrodes C & D in Panel 2 The anode and reference electrodes were the same make and model as those used in the laboratory trial. The panel area was 4.5 m × 2 m, with 16 mm reinforcement, 8 bars running horizontal and 24 vertical bars evenly spaced. The system was energised and current provided for a three month period on each