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‘Innovative approaches to electrochemical remediation of concrete’

The corrosion of reinforcing steel in concrete structures is a global problem. A number of highly technical repair materials are now available to repair concrete structures suffering steel corrosion damage. Often, however, an incipient corrosion problem remains in untreated chloride contaminated areas which may lead to subsequent failure.

This paper describes both galvanic and impressed current systems, which can be applied to corrosion susceptible structures, which focus on addressing the fundamental electrochemical nature of corrosion.

A galvanic system for enhancing longevity of patch repairs to reinforced concrete is discussed with particular reference to its ability to overcome incipient anode formation. Data to support cost effective extension of this galvanic technology to globally treat corroding reinforced concrete structures will be presented. An alternative impressed current solution to treating contaminated reinforced concrete structures will also be discussed.

Keywords:
Reinforcement corrosion, incipient anode effect, electrochemical techniques, chloride extraction, realkalisation, cathodic prevention, galvanic protection

1. INTRODUCTION

The large majority of reinforced concrete structures continue to perform as designed offering a low maintenance solution. However, due to exposure to adverse conditions not anticipated at inception or inadequate specification/construction practices, concrete structures can fail prematurely. It is not uncommon, therefore, to see extensive corrosion of reinforcing steel in such diverse structures as industrial & residential buildings, car parks, ports and power & desalination plants which require repair of some form. Around 45% of the UK construction industry budget is spent on maintenance and refurbishment, and in 1998, the size of the UK concrete repair industry was estimated to be in excess of £1bn [1].

In a reinforced concrete structure the alkaline nature of the hydrated cement phases leads to the formation of a passive oxide layer on the surface of the reinforcing steel that effectively reduces corrosion to negligible levels. However, the finite permeability of concrete allows the ingress of chemical agents which lead to a breakdown in the protective passive layer and subsequent corrosion of reinforcing steel [2]. The two most commonly encountered processes leading to rebar corrosion are (a) carbonation in which a pH reduction in the concrete pore solution is induced by the action of carbon dioxide and (b) chloride attack [3]. These processes lead to breakdown of the passive oxide layer and subsequent formation of expansive corrosion products, which can lead to cracking and spalling of the concrete surface.

Chloride attack on reinforcing steel can be as a result of chloride salts which have diffused in from the external surface, for example, wind-blown sea salt, or from cast-in chloride salts. Above a certain chloride level threshold [4], steel corrosion is initiated. According to Tutti [5], initiation is followed by a propagation period, which eventually leads to cracking and spalling of the concrete.

The techniques employed in concrete repair have developed over the past few decades, and variety of solutions to the problem of reinforcement corrosion now exist [6]. More recently, an improved understanding of the corrosion process has led to the development of electrochemical techniques, which attempt to address the actual cause of the problem rather than the symptoms.

This paper describes a number of electrochemical treatments for protecting reinforced concrete structures, with examples of installations and supporting data obtained.

2. CONCRETE REPAIR OPTIONS

Understanding the cause and assessing the extent of reinforcement corrosion is the key to selecting an appropriate repair solution. A number of electrochemical corrosion control techniques are now available to the building owner or engineer to prolong the life of the structure and minimise future maintenance. These solutions have been developed to meet the wide range of cost/lifetime requirements of the building owner, and include Galvanic Protection, Impressed Current Cathodic Protection (ICCP), Realkalisation and Chloride Extraction.

Some of these techniques may be used proactively to prevent corrosion damage from occurring, whilst others may be used to complement traditional structural concrete repairs in order to ensure durability.

2.1 DISCRETE GALVANIC ANODES IN CONCRETE PATCH REPAIR

The most common method of addressing spalling concrete on structures is reinstatement with a formulated repair mortar. This involves removal of loose concrete and breakout to and beyond steel, removal of steel corrosion products through mechanical cleaning, priming, and application of the repair mortar. More recent technical advances have led to the development of mortars with low shrinkage characteristics to improve patch longevity.

While this repair patching method addresses the immediate problem, it can lead to the development of a phenomenon called the ‘incipient anode’ or ‘ring anode’ effect. The incipient anode effect is a phenomenon whereby new corrosion cells develop next to, or surrounding the repairs, and is effectively instigated by the action of placing patch repairs in a chloride contaminated structure.

Incipient anode corrosion results from an electrochemical incompatibility between the repair and the substrate concrete. The differences in electrical potential of the steel in the two environments results in a driving voltage that can lead to the formation of a corrosion cell on the steel. Gu [7] details the mechanisms involved.

A potential solution is to break out all contaminated concrete. This is effective but very expensive, dusty, noisy and disruptive and may necessitate temporary propping of the structure due to mass concrete removal.

In order to overcome this problem, a zinc-based galvanic sacrificial anode was developed, which is designed to be incorporated into a patch repair [8].

A sacrificial anode design comprises a sacrificial zinc alloy, surrounded by a specifically formulated mortar to optimize activity [9]. The mortar facilitates zinc dissolution by preventing the formation of an interfering passive layer, which allows the less noble zinc to corrode and sacrificially protect reinforcing steel to which it is attached, thus countering the formation of anodic sites outside the periphery of the patch repair. In this case, the cathodic steel just outside the patch repair area will remain cathodic after reinstatement, even though it is in an environment containing chloride.

Twelve of the sacrificial anode units were installed at the periphery of two patch repairs on a bridge beam in the UK. Considerable corrosion of the steel reinforcement had lead to spalling which was due to contamination from de-icing salts caused by leaking bridge deck joints. Chloride levels were 0.8 to 2.2% by weight of cement. One patch measured 2m by 0.68m and the second measured 0.35m by 0.68m. Each patch contained eight and four units respectively. Figure 3 shows the total current output and current densities for the system over a period of 1225 days. Current density was calculated by extending to an area of influence of 400mm outside the patch area.

The current density varies between 1-5mA/m^2 of steel (Figure 1), following a seasonal pattern in which current increases when the environment becomes more aggressive and vice versa. A current density of 0.4mA/m^2 has been shown to prevent initiation of steel corrosion in reinforced concrete containing 2% chloride by weight of cement [10] and is in the region of cathodic prevention proposed by Pedeferri [11]. Visual examination of this bridge beam shows no signs of incipient anode induced failure 1225 days after installation.

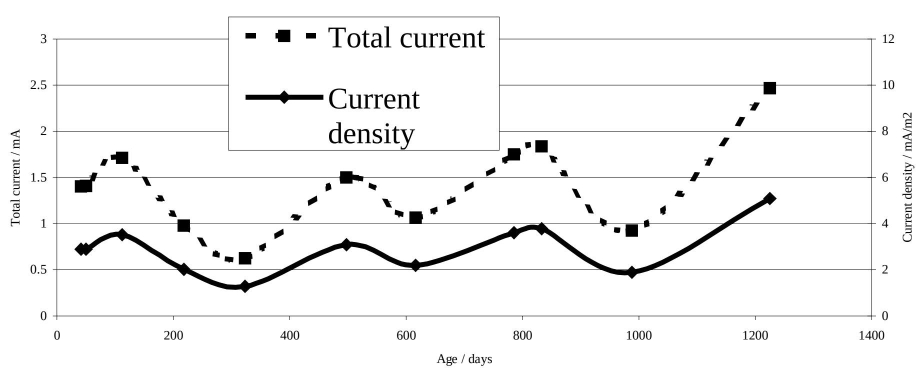

Figure 1. *Total current and current density from 12 sacrificial zinc units installed into a repaired UK bridge beam suffering chloride attack.*

Additional independent data has been gathered on this sacrificial anode repair system in Japan, in which significant steel potential shifts induced by the sacrificial anode were clearly demonstrated in laboratory tests and bridge repairs [12].

2.2 GLOBAL GALVANIC PROTECTION

It is generally the case on reinforced concrete structures, that chloride contamination is likely throughout larger areas of the structure than those where spalling has initiated and in any long-term maintenance proposal this should be addressed by some form of treatment aimed at arresting further corrosion activity. A logical step is to extend the galvanic corrosion protection principle to areas outside these repair patches.

To this end, an enhanced sacrificial anode has been designed in a form which facilitates discrete installation into pre-drilled holes in reinforced concrete [13]. This comprises cylindrical, mortar encased zinc anodes wired together in sequence and inserted into the pre-drilled holes in a grid configuration. When connected to the steel reinforcement the grid impresses a galvanic current through the steel, suppressing anodic reactions and controlling corrosion. Two installations are described below, on a structure suffering chloride attack and one in which carbonation posed the threat.

Condominium, Florida, USA

Condominiums on the Florida coastline suffer from chloride contamination delivered by saltwater deposition. The relatively high temperatures and humidities appear to accelerate the time to initiation of reinforcing steel corrosion and a number of the structures are now suffering from concrete deterioration.

A condominium, exhibiting spalling problems, was selected for application of global galvanic anode protection. A preliminary investigation of the affected balconies revealed variable chloride contents, generally above accepted chloride threshold values, with a range of half-cell potential values from –45mV to – 515mv (v copper sulphate ref) reflecting variable corrosion activity, which reflects visual observations.

Two balconies were initially selected, and treated with 47 galvanic units. In addition to current measurements, Ag/AgCl reference electrodes buried in the structure were used to monitor steel potentials using a remote monitoring system. A summary of data collected is shown in Table 1.

Age/days	**Current density (mA/sqm)**	**24 hour Depolarisation (mV)**
18	22	88
162	10	46
684	7	228

Table 1. *Depolarisation/current data for sacrificial units installed on a condominium*

The data from Table 1 shows that the galvanic anodes are providing significant current output and calculation of current density on the steel surface indicate that is offering corrosion control to the balconies.

The 24 hour depolarisations taken vary but show that the NACE 100mV criterion [14] is met at 684 days of operation. The variation in depolarisations are associated with the conditions at time of tests, as discussed previously (see figure 1) and the increasing effect of the current on the steel environment.. The magnitude of polarisation is such that it represents a significant reduction of the corrosion current and therefore corrosion rate. The trial indicated that corrosion control could be achieved on this structure, which allowed the remainder of the balconies to be renovated using the same technique.

Historic structure, UK

A second installation of discrete galvanic anodes consisted of 12 units installed on a 1920's built structure in the UK. The concrete was carbonated to a depth of 60-80mm with cover depth of 10-55mm, and significant areas of spalling were evident prior to repair. An actively corroding area of dimensions 2m by 1.9m was treated. In addition to monitoring current output, buried Ag/AgCl chloride reference electrodes allowed monitoring of steel potential.

Table 2. *Depolarisation after 24 hours for sacrificial units installed on a UK carbonated historic structure*

Age				
1 month	4 months	6 months	13 months	16 months
276mV	224mV	171mV	147mV	152mV

Current density was measured at 1.0–7.7mA/m^2. According to NACE criteria [14] for operation of cathodic protection systems, 24h depolarisation values demonstrate that the galvanic system is cathodically protecting the reinforcing steel.

3. IMPRESSED CURRENT CATHODIC PROTECTION (ICCP)

ICCP has been used on reinforced concrete structures since the 1970's [6]. ICCP involves passing a current, using an 'inert' anode, through the reinforcing steel. There are several protective effects that are induced on the cathodic steel in concrete when an electric current is passed. They include:

- Lowering the steel potential to more negative values to inhibit the anodic reaction or the dissolution of steel.
- Transporting aggressive anions, such as chloride, away from the steel surface due to the induced ionic current within the concrete.
- The formation of hydroxyl ions on the steel surface which raises the pH, an insoluble oxide film is formed and passive steel is returned.
- Oxygen is consumed on the steel surface and the capacity to support corrosion cells is reduced

One of the features of the system is the permanent requirement for a D.C power source (Rectifier unit) and a permanent anode system to deliver the current. In addition to the cost of initial installation, ICCP requires investment in periodic monitoring to ensure that the system is operating effectively.

Anodes for use in ICCP applications can take a variety of forms dependent on the type of structure to be protected and the practicalities of installation, and can utilise discrete or external anode systems.

3.1 DISCRETE ICCP ANODES

A typical discrete anode ICCP system comprises cylindrical anodes, composed of an inert material, grouted into pre-drilled holes in the structure, connected by a conductor to a DC power unit. It is important that these discrete anodes have an inherent venting system to allow dissipation of oxygen formed during operation. In addition the encapsulant grout should be formulated to optimize dissipation of acid formed on operation [15].

The facility to bury discrete anodes within the concrete structure allows protection of deeply buried steel or multiple steel layers. In addition the applied system adds no weight loading to the structure, and can easily be applied to difficult geometries.

These discrete anodes have been used since 1994, in the protection of steel in concrete and in steel framed buildings. A typical example form the Middle East, is in the renovation of a reinforced concrete basement subject to chloride contamination from the leakage of groundwater through the failed waterproofing barrier.

In an initial trial area, discrete anodes were installed in a grid pattern, at anode separations of 600mm and 1m. Current was applied to these units using a standard rectifier/control unit and half-cell potential measurements were taken at various times using a copper/copper sulphate reference electrode, to determine the extent of protection offered by the CP system. Results are summarized in table 3.

Table 3 – *24 hour Depolarisation data from Middle East discrete anode trial.*

Ebonex Anode reference	Distance from Reference Electrode to Ebonex Anode (cm)	24 hour Depolarisation (mV)
A1	40	172
	50	163
	60	69
	70	89
A2	20	195
	50	119
	60	80
	65	79

A3	25	193
	45	102
	60	136
A4	10	158
	45	123
	50	111

The data in table 3 demonstrate that 100mV polarisation required in NACE 0290-90 [14] has been achieved at a minimum distance of 50cm from the discrete anodes, suggesting cathodic protection has been conferred. It is also clear that the influence of the discrete anode unit on steel polarisation decreases with distance as would be expected from the increasing contribution from the concrete resistivity.

The currents were applied in this particular case for a relatively short period. It is important to consider the additional benefits of long term treatment which will result in anodic polarization of the steel to more passive depolarized potentials, as described by Glass et al [16].

4. CONCLUSIONS

- A range of electrochemical solutions is now available which offer a significant extension of the longevity associated with conventional patch repair.
- Galvanic systems offer a simple targeted approach to concrete repair which is ‘self-powered’ without the need for monitoring
- The level of current outputs measured, 0.5-7mA/sqm for the galvanic systems, is in the ranges that would be expected for cathodic prevention/protection of reinforced concrete
- Galvanic protection has been shown to impart significant levels of steel polarization.
- Discrete anodes can be effectively used as part of an ICCP system which meets NACE 0290 criteria. Discrete anodes offer benefits in current distribution in geometries such as bridge beams.

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