HYBRID ELECTROCHEMICAL TREATMENT APPLIED TO CORROSION DAMAGED CONCRETE STRUCTURES*

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ABSTRACT

A major cause of damage to reinforced concrete structures is corrosion of the steel. To address this problem a simple but powerful electrochemical treatment has been developed. Steel passivity is firstly restored using a brief high current. This lasts about 1 week. In the process corroding sites are moved from the steel to an installed anode system. Low maintenance galvanic protection is then provided. This requires no user input to function. A single anode system consisting of a hybrid of impressed current and sacrificial technologies is installed to deliver the protection current in both phases. The anode system will typically contain enough charge to provide a galvanic protection current for 50 years. The electrochemical treatment has now been applied to more than 10 structures around the world including bridges, car parks, marine structures and buildings and the early trials in heavily chloride contaminated concrete continue to deliver outstanding performance. Monitoring has been tailored to meet end user requirements and in every case tested, the steel in the concrete has been rendered passive.

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Introduction

Many reinforced concrete structures suffer from corrosion damage. Causes include salt ingress into the concrete and carbonation of the concrete. Treating this damage presents problems because of the associated changes in the concrete cover. Corrosion is an electrochemical process and one technology that has been successfully applied to arrest corrosion is a combination of electrochemical treatments termed a hybrid electrochemical treatment. It has provided a cost effective solution on several structures around the world. This paper reviews the use of this hybrid treatment to arrest and prevent corrosion damage and provides examples of its use.

Steel Passivity, Corrosion and Protection

Concrete is normally highly alkaline and steel in this environment is protected by a passive film. Figure 1 shows a section of the potential/pH diagram for iron and its oxides in water (1). Steel in concrete is initially located in a region of pH greater than 12 where a passive oxide film will form.

Passive films are not perfect and some reaction of iron and water does occur. This is usually negligible. However, in the presence of chloride ions, hydrochloric acid is produced (2) and localised pitting corrosion results. pH values as low as 4 have been measured at corroding sites on steel in what is otherwise a very alkaline concrete environment (3). Furthermore carbonic acid is produced by the reaction of carbon dioxide in the air with water in the concrete (carbonation) and this can also reduce the pH at the steel.

The production of acid is considered to be an essential feature leading to significant corrosion damage on passive steel (4). This is true for both carbonation and chloride induced damage. This process is illustrated in Figure 1. Steel moves from a region where insoluble oxides are the most stable product to a region where iron is soluble in the process of corrosion initiation.

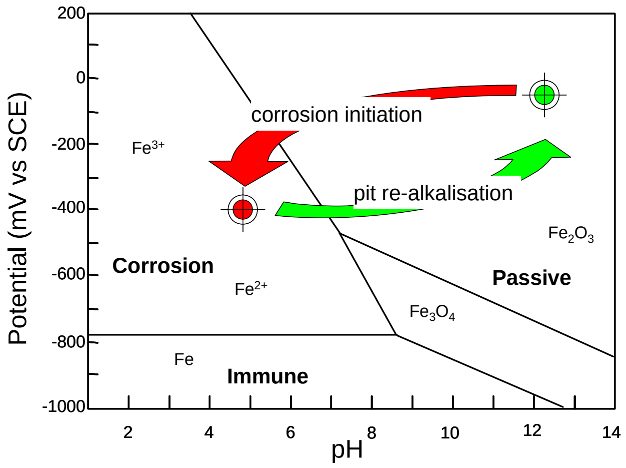

Figure 1 Model of corrosion initiation and arrest showing the stability of iron and its corrosion products.

One of the effects of an electrochemical treatment is to produce hydroxyl ions on the steel raising the pH. A brief high current treatment, delivered using a DC power supply, may therefore be used to rapidly re-alkalise the acidic corrosion sites. This re-alkalisation process is also illustrated in Figure 1 and would lead to a restoration in steel passivity. It is termed pit re-alkalisation when localised pitting corrosion is arrested (5).

In a recent analysis of the available literature it was shown that applied charge densities below 100kC/m^2 would be sufficient to induce a change in the environment at the steel leading to the arrest of a corrosion process in chloride contaminated concrete. Furthermore, such a charge may be delivered more easily using a sacrificial metal as an impressed current anode (5). Thus the temporary electrochemical treatment may be delivered in a relatively short period using a sacrificial anode and a power supply.

To ensure sustained steel passivity a small galvanic current may be applied after the initial re-alkalisation process. This may be facilitated by installing the sacrificial anode for long term use in the concrete structure. Galvanic protection is low maintenance and requires no user input to function. A small galvanic current will continue to generate hydroxide at the steel at a low rate (6). This two-phase treatment is referred to as a hybrid electrochemical treatment.

Hybrid Electrochemical Treatment

Comparison with Existing Technologies

The basis for the hybrid treatment technology is provided by the inhibitive properties of hydroxyl ions. These are first generated at a rapid rate on the steel to arrest the corrosion process and then maintained with a low level galvanic treatment. Corrosion sites are effectively moved from the steel to the installed anode (7).

The temporary impressed current phase is compared with chloride extraction in Figure 2. Figure 2(a) shows a chloride extraction treatment. The power supplies, electric cables and anode system consisting of a steel mesh in wet cellulose fibre, are temporary fixtures and are removed at the end of the treatment process which typically lasts 6 weeks.

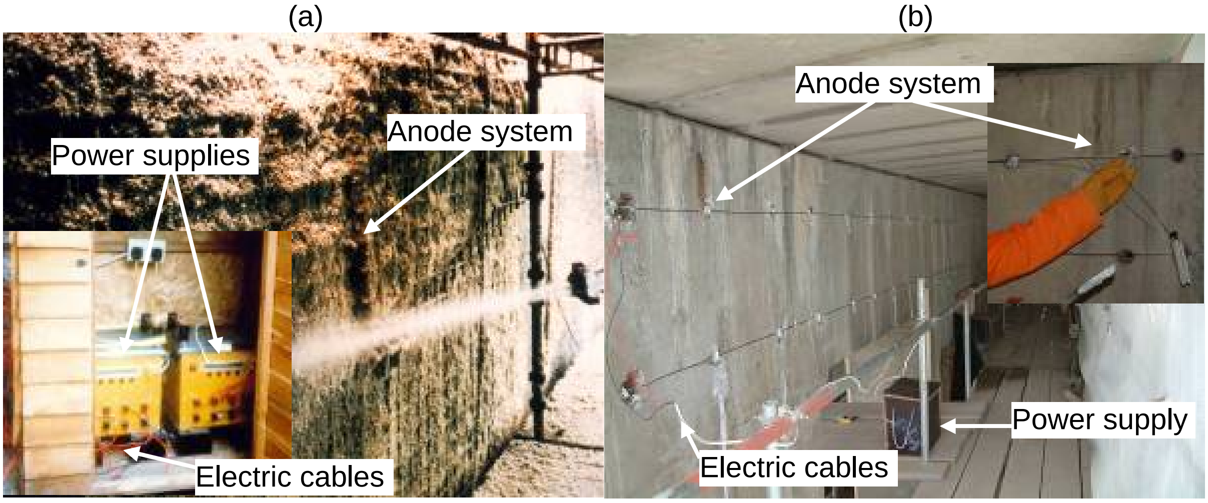

Figure 2 Comparison of the temporary treatments of chloride extraction (a) and pit re-alkalisation (b) applied to reinforced concrete.

Figure 2(b) shows an example of the temporary treatment phase to arrest a corrosion process in the hybrid technology. The anode system is permanently installed while the power supply and some electric cables are removed at the end of the treatment. The temporary power supply is typically removed after 1 week of treatment. After the anode system has been installed, it is no longer necessary to keep the scaffolding in place to deliver the temporary treatment as the power supply can be located at any convenient position and the anode will not be removed. If the anode system was located on a concrete surface required for access such as a car park ramp, access need only be restricted while the anode system is installed and access to the surface need not be restricted to deliver the treatment.

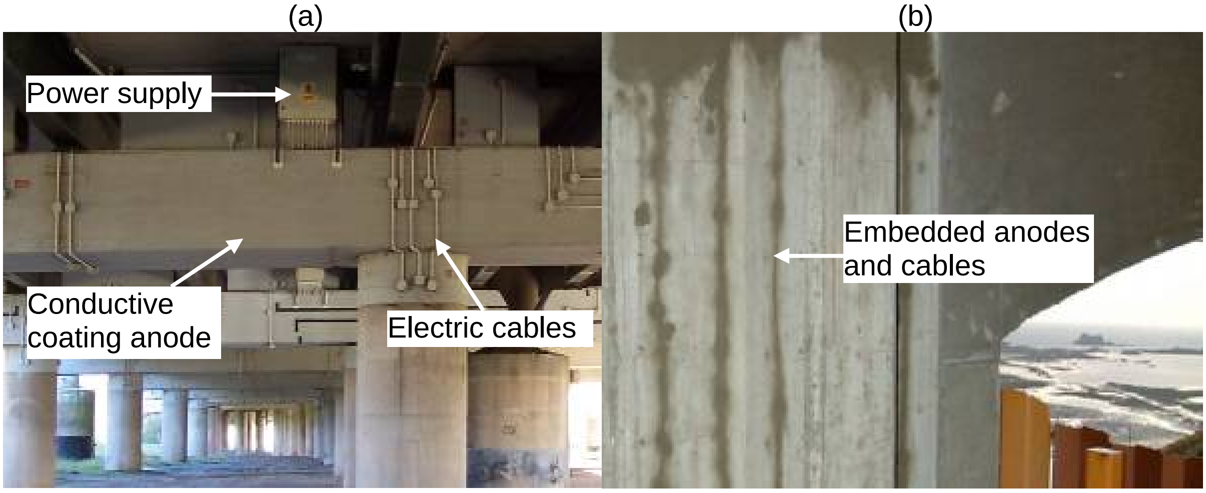

Figure 3 Comparison of impressed current cathodic protection (a) and galvanic protection (b) applied to reinforced concrete.

The long term galvanic phase of the hybrid technology is compared with impressed current cathodic protection in Figure 3. Figure 3(a) shows an example of the power supply and electric cables that form part of the permanent installation making up a cathodic protection system. These are not required in the galvanic phase of the hybrid technology and the limited cabling that connects the sacrificial anodes to the steel may be buried within the concrete structure (Figure 3(b)).

Installation Practice

Figure 4 shows a practical installation during the impressed current phase of the hybrid electrochemical treatment. In this example the Duoguard 500 product is used.

Figure 4 Stages in a hybrid treatment process showing (a) locating the steel, (b) installing the anode system (c) the impressed current treatment and (d) the galvanic protection phase.

The steel is located with a cover meter to select the position of the anodes Figure 4(a). The anodes are placed as far from the steel as possible to promote current distribution. The holes for the anodes are then formed using a method that depends on the anode used. These will then typically be filled with a backfill supplied as part of the anode system Figure 4(b) and the anodes are inserted into this backfill.

A temporary power supply is then used to deliver the first phase of the treatment to change the environment at the steel to a less aggressive environment Figure 4(c). The charge delivered is dependent on the aggressive nature of the concrete environment with more charge being conveniently delivered in more aggressive environments as these also promote higher anode current outputs. This treatment is typically delivered in one week and depends on whether the anodes are covered with a repair mortar.

After this brief initial treatment, the anode is electrically connected to the steel. Any exposed cables and anodes are covered with a repair mortar Figure 4(d). The system components do not need to be accessible. The galvanic generation of hydroxide then sustains steel passivity.

Acceptance Criteria

The system operates by inducing and maintaining conditions in the concrete that lead to steel passivity. Thus a preferred acceptance criterion is to show that the steel corrosion rate is negligible. The focus of the criterion is the condition of the structure rather than the behaviour of the protection system.

Corrosion rates are commonly measured using the polarisation resistance method. The same theory may be used to measure corrosion rates during the galvanic phase of the hybrid treatment on condition that the approximations requiring small potential changes are not adopted (7). This improvement allows large changes to be used in field measurements.

An example of the calculated corrosion rate as a function of the change in potential (potential shift) induced by an applied current density of 2 mA/m^2 is given in Figure 5. Similar curves can be calculated for other applied current densities. Corrosion rates below 1mA/m^2 represent a steel section loss of less than 1mm every 1000 years and are generally considered to represent passive steel. Corrosion rates rising above 2 mA/m^2 are considered to represent and increasing risk of localised corrosion activity.

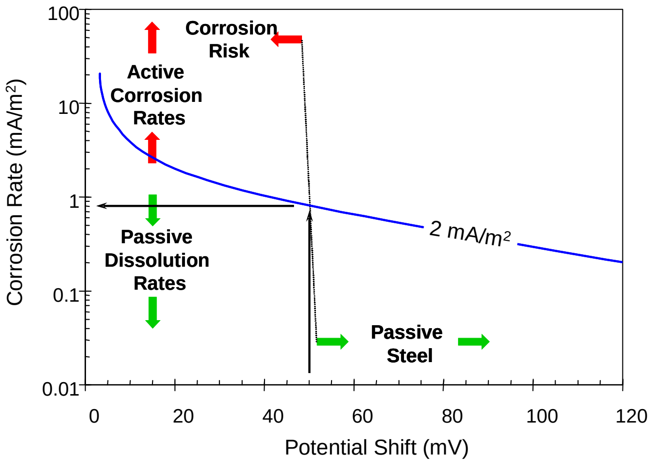

Figure 5 The corrosion rate plotted as a function of potential shift and current density together with an example of its interpretation.

In practice, the data for the corrosion rate calculation can be obtained from the current density and potential shift induced during the galvanic phase of the treatment. A conservative estimate of the potential shift is given by the potential decay measured using a reference electrode and the current density may be obtained by measuring the current off a small segment of the anode system that delivers current to the steel near the reference electrode.

Another method of assessing performance uses potential mapping. This is a non-destructive technique that identifies locations where anodes are active. Anodes should only be found at the location of the installed anodes and it is preferable that these installed anodes influence the potential gradient at all points between the installed anodes. The absence of anodes between the installed anodes indicates that the steel corrosion rate is negligible.

While monitoring is always advisable, monitoring is not required for the system to function. Monitoring intervals may therefore be tailored to fit in with other structure requirements. For example the monitoring interval can be tailored to fit in with annual or principle bridge inspections and provide additional data on the structure at this time.

Anode Life

The life of the sacrificial anodes can be estimated from their charge capacity and current output. One Duoguard 500 anode holds a charge of approximately 130 Amp.hrs. 50 years of cathodic prevention at a current density of 1mA/m^2 is equivalent to a charge of 450 Amp.hrs/m^2. Approximately 10% of the anode system is consumed in the impressed current phase.

Data from practical installations has indicated anode lives will exceed 50 years in many cases. This is related to the chloride content of the concrete and in aggressive conditions that promote high galvanic currents, the anode may be consumed more rapidly.

Field and Laboratory Data

System Performance

The performance of the hybrid electrochemical treatment has been assessed using data obtained from both laboratory studies and field installations. The output of the anode system responds positively to variations in chloride content, moisture and temperature. These factors also determine the aggressive nature of the environment to steel, and high current outputs are delivered in both impressed current and galvanic phases in concrete environments that are aggressive to reinforcing steel. In all field installations tested to date, the steel has been rendered passive by the treatment.

Figure 6 shows the current delivered by one Duoguard 500 anode to 0.25 m^2 of steel in a concrete block containing 4% chloride by weight of cement in a dry laboratory environment over a 2 year period. The anode was initially driven with a 12V DC power supply to deliver the temporary impressed current treatment and then the power supply was removed and the anode was connected to the steel (9).

The current driven off the anode by the power supply was approximately 50 mA (8500 mA/m^2 of anode surface) in this aggressive environment. In galvanic mode, the current decayed to approximately 1 mA (170 mA/m^2 of anode surface). This current output has been sustained for more than a year and is relatively high for a preventative treatment where much lower values are considered to be adequate. The chloride in the concrete is one of the more important factors sustaining this high current output.

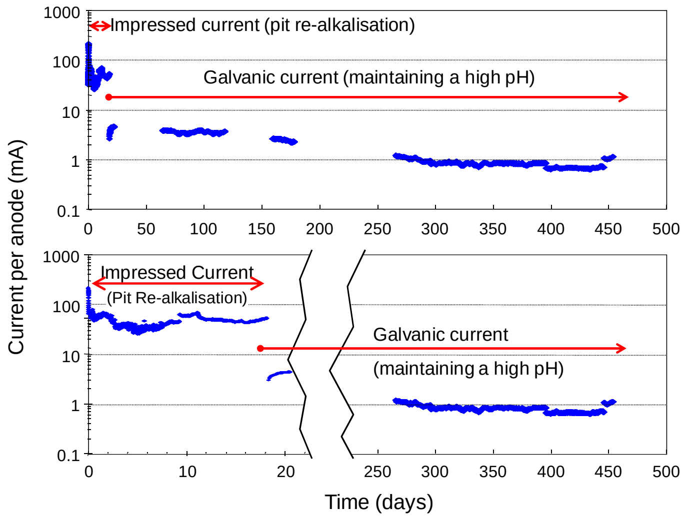

Figure 6 The current delivered by one anode in a hybrid treatment applied to 0.25m^2 of steel in concrete containing 4% chloride by weight of cement.

Figure 7 shows the steel potential prior to applying the hybrid treatment and a steel potential decay measured 60 days after the application of the impressed current phase in the concrete specimen described above. The open circuit potential of the steel shifted to significantly more positive values indicating that the corrosion was arrested by the treatment. This was confirmed by the corrosion rate measurement which indicated that the steel corrosion rate at this point was less than 0.25 mA/m^2. Subsequent corrosion rate measurements have indicated that the corrosion rate is now less than 0.1 mA/m^2. These are negligible corrosion rates.

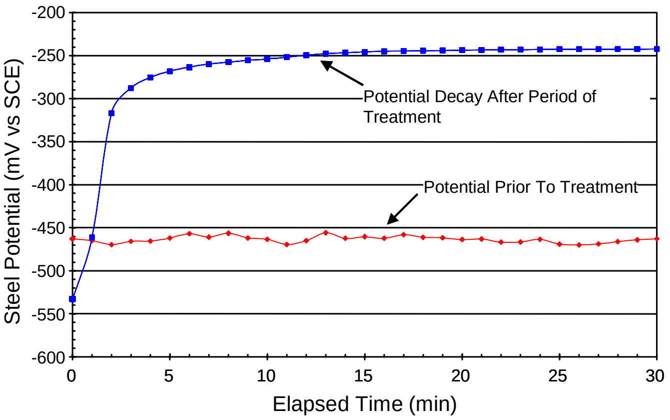

Figure 7 Steel potential prior to the hybrid treatment and the potential decay on interrupting the treatment after 60 days.

The effect of temperature on anode current output in a car park column 20 days after ending the impressed current treatment is shown in Figure 8. Current is delivered more readily in warmer conditions and higher current densities were measured during the day.

Figure 9 shows the potential of the galvanic anode - steel couple and the measured corrosion rates recorded during the first year after the initial impressed current phase of a treatment applied to a bridge structure. The bridge suffered from chloride induced corrosion arising from the use of de-icing salts and approximately 300 m^2 of steel was treated. The data suggests that the steel is passive. The corrosion rates are negligible and the potentials are moving to more passive values.

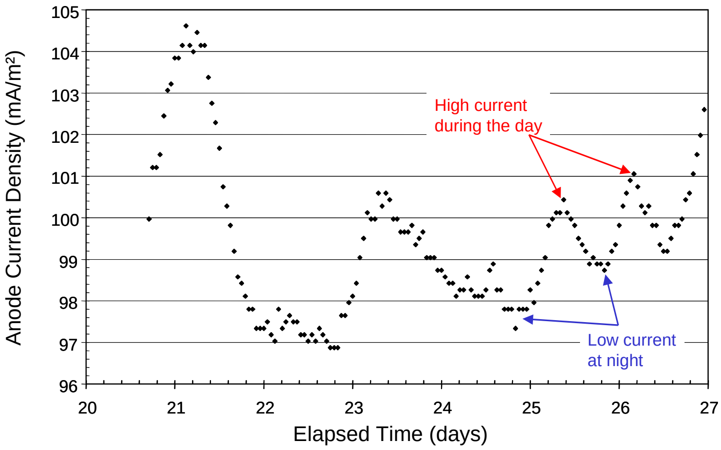

Figure 8 The effect of temperature on anode current output in a car park structure.

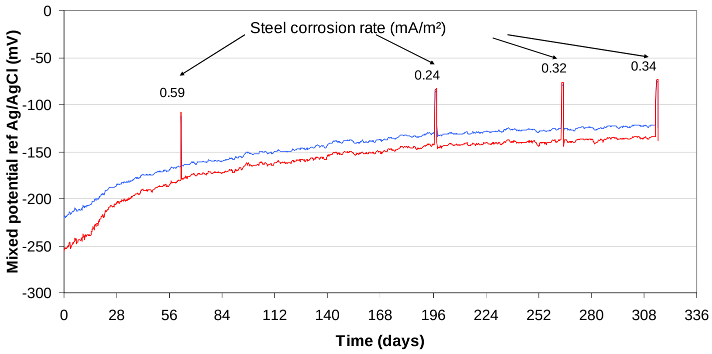

Figure 9 Measured potentials and corrosion rates in a bridge structure.

Field Installations

The hybrid electrochemical treatment has now been applied to more than 10 structures around the world. Figure 10 shows a selection of the structures that have been subjected to the treatment. These include bridges, car parks, marine structures and buildings.

Figure 10 A selection of the structures that have been treated with the hybrid electrochemical treatment.

Figure 11 Reinforced concrete beams in a marine structure prior to (top) and after repair and treatment (bottom left and right).

An example of a marine installation is shown in Figure 11. The soffits of these reinforced concrete beams are exposed at high tide to saline estuary water which has cause the steel to corrode. The beams were repaired with sprayed concrete and a Duoguard 500 system was installed in the parent concrete just above the repair area. During the galvanic phase of the treatment, potentials were measured in a line around the circumference of one treated beam to include the repaired soffit and two adjacent sides. This potential data is plotted in Figure 12. The location of the anodes is clearly evident and the data shows that the steel potential was influenced by the anodes at all locations between the installed anodes.

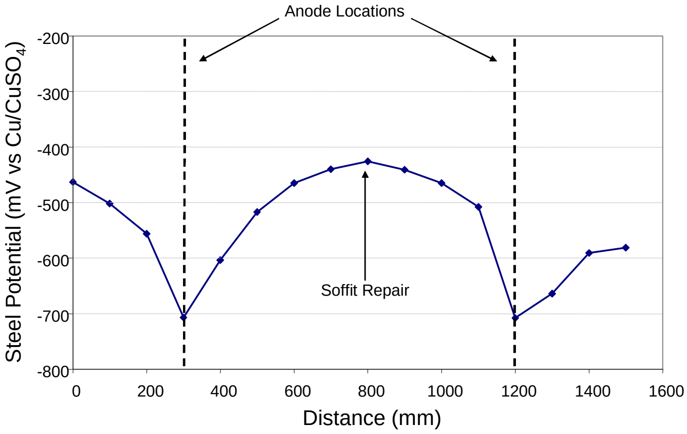

Figure 12 Potential gradient measured on the circumference of a treated beam in Figure 11.

This installation represents an example of a targeted application of the treatment. The steel in repair material does not normally need intensive treatment, as repair materials are chloride free. The highest residual corrosion risk is in the concrete adjacent to the repair and this is one of the best places to locate the anodes to deliver the treatment.

Some clients have required a strategy to deal with any risk of protection system failure even when sacrificial anodes are used. In the above installation the designer included such a strategy within the system design. The anodes were connected to the steel at accessible locations allowing the temporary impressed current treatment to be re-applied in the future using the existing anode system and a temporary power supply.

Hybrid Treatment Features

Several advantageous features of the hybrid electrochemical treatment have been identified in the review above. These include:

- the power to rapidly arrest an aggressive corrosion process,
- a system that can be targeted to an area of need,
- the limited requirement for access to the affected concrete,
- monitoring that can be tailored to end user requirements, and
- a strategy to deal with the risk system failure.

The power to rapidly arrest an aggressive corrosion process is provided by the brief impressed current treatment. The system can be targeted because the local protective current is determined by the local environment and is not dependent on an external power source. The access requirement is limited because access to the anode is not necessary after it has been installed and the treatment can be delivered using a remote, temporary power supply. Monitoring is not critical to system function and the option of re-applying the temporary treatment is available as a contingency. These features provide the hybrid electrochemical treatment of corrosion damaged concrete with a unique combination benefits.

Conclusions

A simple but powerful hybrid electrochemical treatment has been developed to address the problem of corrosion induced damage in reinforced concrete. Steel passivity is firstly restored using a brief high impressed current lasting approximately 1 week. In the process corroding sites are moved from the steel to an installed anode system. Low maintenance galvanic protection is then provided. This requires no user input to function.

A single anode system consisting of a hybrid of impressed current and sacrificial technologies is installed to deliver the protection current in both phases. The anode system will typically contain enough charge to provide a galvanic current for 50 years.

The electrochemical treatment has now been applied to more than 10 structures around the world including bridges, car parks, marine structures and buildings and the early trials in heavily chloride contaminated concrete continue to deliver outstanding performance.

An acceptance criterion has been based on the achievement of negligible steel corrosion rates. Monitoring has been tailored to meet end user requirements and in every case tested, the steel in the concrete has been rendered passive.

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