MATEC Web of Conferences **361**, 02005 (2022) https://doi.org/10.1051/matecconf/202236102005
Concrete Solutions 2022

Long term performance of reference electrodes for cathodic protection of steel in concrete

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Abstract. This paper will report on long term behaviour of potential sensors used in cathodic protection of steel reinforcement in concrete. Cathodic protection (CP) systems, both impressed current CP (ICCP) and galvanic CP (GCP), need regular testing to establish the quality of protection. In addition, ICCP may require adjustment of output voltage or current. Various types of potential sensors have been used in relatively large numbers, comprised of true reference electrodes (RE) based on silver/silver chloride or Mn/MnO_2 and decay probes (DP) based on a.o. activated titanium. Failures may occur due to loss of contact, drying out or cable defects. Test methods for potential sensors are discussed. Monitoring of about one hundred CP systems with several thousands of potential sensors over more than ten years allows to analyse their performance and failures. It appears that limited numbers of potential sensors fail over time, but in some cases an insufficient number of working potential sensors are left to properly monitor a CP system or zone. It is recommended to install more potential sensors than strictly needed in order to allow for failures and to maintain testability and save the high cost of installing new potential sensors later.

1 Introduction

Cathodic protection (CP) of steel reinforcement has become the major and most successful method to stop or prevent corrosion in concrete. Over time, many reinforced concrete structures develop corrosion of the embedded steel, due to long-term exposure to aggressive influences such as chlorides from sea water and de-icing salts or the effects of mixed-in chlorides; in some cases aggravated by carbonation [1, 2]. Steel corrosion causes cracking and spalling of concrete and steel cross section loss, compromising serviceability and eventually structural safety. Consequently, repair and protection of concrete structures has become a major industry in the past 40 years. However, in many cases conventional methods of concrete repair have been shown to be ineffective or not durable [3, 4]. CP on the other hand, provides an effective and durable method for protection of steel in concrete.

CP of concrete structures was developed in the USA in the 1970s [5] and introduced in Europe in the 1980s [6]. In the USA, many concrete bridge decks were damaged by corrosion due to chloride ingress from de-icing salts. Early types of anodes were applied with varying results; many of these early anode types have been discontinued [7]. Later, new anode materials became available, such as activated titanium and conductive coatings, variants of which are still widely used today; sacrificial (galvanic) anodes were introduced in the late 1990s. From about 1985 in the UK [6], Italy [8], Norway [9, 10], Denmark, Switzerland [11, 12] and The Netherlands [13] application of CP to concrete increased. A growing number of systems are being installed more recently in Germany, France, Belgium and Switzerland. Long term performance and an overview of interventions have been analysed [14, 15].

An essential element of every CP installation is the monitoring system, comprised of reference electrodes (RE) and other probes for regular testing of the quality of protection. Without proper monitoring, sufficient protection cannot be guaranteed. This paper reports on an analysis of the long-term performance of such sensors based on the first authors' involvement in monitoring of a large number of CP systems in The Netherlands.

2 Background

Reinforcing and prestressing steel in concrete are normally passivated due to the high alkalinity in the pore solution, caused by dissolved potassium and sodium hydroxides and buffered by solid calcium hydroxide, at pH values above 13. With passivation, corrosion is negligible and very low rates of oxidation and reduction occur. In aerated concrete, potentials of about +100 to -100 mV versus a saturated calomel electrode (SCE) are present. Lowering of the pH due to carbonation, a reaction with carbon dioxide from the atmosphere, or the presence of chloride ions above a certain threshold concentration causes depassivation and initiation of corrosion. Subsequently anodic (oxidation) reactions and cathodic (reduction) reactions are strongly accelerated

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compared to the passive state, respectively described by the following equations:

$$Fe \rightarrow Fe^{2+} + 2\ e \quad (1)$$

$$2\ H_2O+O_2 + 4\ e \rightarrow 4\ OH^- \quad (2)$$

With chloride induced corrosion localised or pitting attack develops and anodic sites may be small; locally the potential drops several hundreds of millivolts and the pH drops to 2-3 [16, 17]. Cathodic potentials remain in the more positive ranges; strong potential gradients develop between anodic and cathodic regions that further accelerate corrosion.

The basic principle of cathodic protection is shifting the steel/concrete interface potential difference to more negative values by injecting a direct current, slowing down oxidation reactions (eq.1), accelerating reduction reactions (eq.2) and reducing potential gradients along the steel. In concrete, shifts of a few hundred millivolts are sufficient to move corrosion rates to negligible levels [8]. This is due to various favourable effects of current flow: increased cathodic reactions produce hydroxyl ions and increase the pH at the steel/concrete interface and negatively charged chloride ions migrate away from the steel/concrete interface. It follows that the potential difference between the steel and the concrete, the “steel potential”, is a dynamic entity, indicating the corrosion state and varying with long term effects of current flow. Consequently, measuring the potential plays a major role in controlling CP.

In a CP system the current is injected into the concrete from an electrode installed on the concrete surface or in the cross section, called the anode, causing the interfacial potential to shift. At this anode, oxidation reactions take place that consume hydroxyl ions or that oxidise materials at the anode/concrete interface described by the following equations:

$$4\ OH^- \rightarrow 2\ H_2O + 4\ e \quad (3)$$

$$M \rightarrow M^+ + e \quad (4)$$

Reaction (3) may cause acidification and possibly loss of anode/concrete bond by dissolving the hardened cement paste; reaction (4) oxidises galvanic anode materials or carbon particles in conductive coatings. Possible side effects at the cathode are accumulation of alkali ions due to ionic migration; and hydrogen evolution according to an additional cathodic reaction that occurs when insufficient oxygen is available to sustain eq. 2:

$$2\ H_2O + 2\ e \rightarrow H_2 + 2\ OH^- \quad (5)$$

Hydrogen evolution at the surface of prestressing steel may cause its embrittlement. Reaction (5) can be avoided by limiting the current density at the prestressing (or duct) surface. As this reaction only occurs at very negative potentials, typically -1100 mV versus SCE, monitoring the steel potential can be used as a safety measure. At more positive potentials than about -1000 mV, only reaction (2) is possible and hydrogen evolution according to eq. 5 does not occur. For more background information see [1].

3 Design and operation

Two basic types of CP systems have been used: impressed current CP (ICCP) and galvanic (sacrificial) CP (GCP). The main components are illustrated in Figure 1. In ICCP a low voltage DC power source drives the current. The anode consists of a material that is not (or only slowly) consumed, such as activated titanium (covered with noble metal oxides, Mixed Metal Oxide, MMO) or a conductive coating.

Activated titanium has the shape of a mesh embedded in a cementitious overlay on the concrete surface; or of fine mesh strips in boreholes in the concrete cross section or in slots cut in the concrete surface; holes and slots are filled with a cementitious grout. Conductive coatings are polymers filled with carbon particles, applied to the concrete surface and usually covered with a (normal) topcoat. Primary anodes are metal wires that feed the current into the actual anode material; they should be spaced closely enough to avoid large potential drops in the anode system. Cementitious overlays and conductive coatings should be durably bonded to the concrete surface for good long term electrical contact. Achieving good bond requires good surface preparation and proper application and curing are essential.

In ICCP systems, the power source and the anodes are connected through isolated copper cables and anode-copper connections. Cable cross sections should be large enough for limited potential drop. Cables need to be redundant in order to avoid system failure due to (single) cable interruptions, e.g. by vandalism; at least two cables should feed anodes as well as cathodes, with connections as far apart as possible within a zone. Power sources are fed from the normal grid or by solar or wind energy, the latter two backed up by batteries.

In GCP systems the power originates from the electrochemical potential difference between the anode material and the steel. Corrosion of a sacrificial material, normally zinc, provides the current according to

$$Zn \rightarrow Zn^{2+} + 2\ e \quad (6).$$

A GCP system can be made of zinc sheet with an appropriate activator and a conductive adhesive on the concrete surface; or by embedding zinc probes with activator inside cavities or boreholes in the cross section. Activators are needed to keep the zinc corroding; they are proprietary formulations based on alkalinity, complexing agents or halides. Zinc anodes are connected to the reinforcement using copper wires.

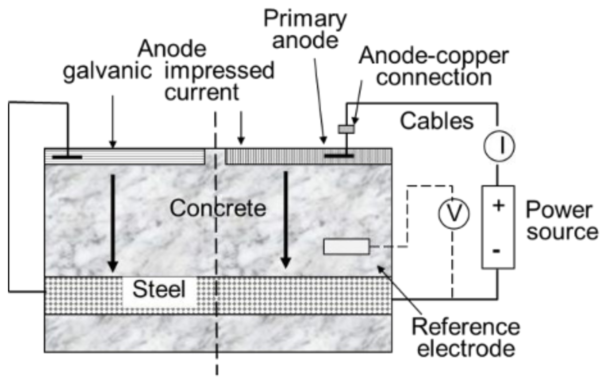

Fig. 1. Main components of galvanic (left) and impressed current (right) CP systems.

A CP system can be divided into separately controlled parts called zones, if current densities between different parts of a structure are anticipated to be different; or for practical reasons. Current densities are affected by differences in concrete electrical resistivity due to different exposure to precipitation or different cement types having been used [13, 18]. Practical reasons can apply to avoid large zones with poor controllability or a low capacity of available power units. In field projects, zones can be as large as many hundreds of square meters, or as small as 10 – 20 m^2 or even smaller (for one example see below).

Basic design of CP is based on a current density of 20 mA/m^2 of steel surface, as a rule of thumb. It can be debated if this should concern all steel in the entire concrete cross section or only the steel closest to the surface. Experience shows that most CP systems operate at much lower current densities, typically of 1 – 5 mA/m^2 (steel surface). However, the current density per unit of concrete surface area can be quite different. Buildings usually contain less than 1 m^2 of steel surface, typically 0.5 m^2 per m^2 of concrete surface. The steel/concrete density of civil engineering structures can be much higher, in particular in areas with higher stresses, typically 1 or more. In practice, impressed CP current is kept as low as possible by applying a low voltage to limit system degradation and negative side effects, while maintaining sufficient protection. In galvanic systems, the current cannot be externally controlled and the zinc consumption rate is determined by concrete resistivity and steel density, which will determine anode working life.

Preventive application of CP for steel in concrete requires lower (design) current densities, in the range of 0.2 – 2 mA/m^2, because preventing corrosion is easier than stopping it [8, 19]. Compared to curative systems, less anode material is needed and current distribution is more favourable.

4 Protection testing

As the current required to achieve protection varies from case to case and possibly with time (wetness, temperature), protection quality needs to be tested regularly. Various protection criteria have been developed. The International Standard ISO 12696 [19] provides the following rules or criteria of which at least one out of the last three c, d and e need to be met:

a) An instant off potential more positive than -1100 mV versus Ag/AgCl/0.5M KCl for reinforcing steel
b) An instant off potential more positive than -900 mV versus Ag/AgCl/0.5M KCl for prestressing steel
c) An instant off potential more negative than -720 mV versus Ag/AgCl/0.5M KCl
d) A potential decay over more than 24 hours of at least 150 mV from instant off
e) A potential decay over a maximum of 24 hours of at least 100 mV from instant off.

All of these criteria except e) need to be tested with a “true” reference electrode (RE) that has a good long term absolute potential stability. Criterion e) can be measured with a simple metallic “decay probe” (DP). True RE’s most widely used are Ag/AgCl or Mn/MnO_2 based, DPs can be based on activated titanium, carbon or other metals. Due to their simpler construction, DPs are less costly than REs.

In practice, the 100-mV potential decay (depolarisation) up to 24 hours is the most widely used criterion for above ground structures. It is measured by interrupting the current for several hours to one day and monitoring the steel potential several times in the interval. In addition, criterion b) must always be used when prestressing steel is present.

ISO 12696 states that a minimum of two REs shall be installed in every zone of a CP system and allows for other sensors, e.g. DPs to be used, in addition to those two REs. This means that according to the Standard using only DPs is not allowed, even if only 100 mV depolarisation is tested for! In contrast, in The Netherlands, DPs have been used without REs being present in a large number of cases over several decades, with full satisfactory behaviour. This is allowed according to a National Recommendation [20]. This Recommendation [20] also states that, in each zone, at least one RE or DP should be placed per 100 m^2 with a minimum of two per zone. This makes sense for larger zones, as testing points can be spread out to better represent variation in aggressive conditions and distribution of protection current. For small zones the cost of two sensors must be compared to the need to get a good impression of protection quality.

Multiple REs or DPs should be embedded at representative locations in each zone. Regular monitoring consists of depolarisation testing at least twice a year and a visual inspection once a year. Monitoring usually starts as part of a maintenance contract between the owner and the contractor who installed the system; such contracts are typically agreed for ten years. Increasing numbers of systems are remotely monitored and/or controlled using dataloggers and modern wireless connection technology. Nowadays more and more systems are being monitored by independent parties, after termination of the original monitoring contract. This implies that proper documentation of the as built system must be available.

5 Specifics of RE and DP

True REs are based on a known chemical (redox) reaction with fixed concentrations of reactants. A silver/silver chloride (SSE) electrode consists of a silver wire covered with silver chloride in a solution of KCl in a polymer enclosure. Another type is based on Mn/MnO_2 in NaOH solution in a stainless-steel enclosure. The electrolytes are in contact with the concrete pore solution through a porous plug, either ceramic or cementitious.

Due to their chemical nature, REs are considered to have a fixed and stable potential. However, SSEs are sensitive to the chloride concentration in the concrete and Mn/MnO_2 electrodes are sensitive to pH changes. Manufacturers state a potential repeatability (between individual electrodes) of +/- 10 mV (SSE) or 25 mV (Mn/MnO_2). They are supposed to drift less than 3 mV in 24 hour and less than 10 mV in 10 years. Once embedded, typical AC resistance to reinforcement is 1500 – 5000 Ω, depending on concrete resistance and distance to a rebar.

Decay probes are pieces of metal, typically activated titanium (MMO coated, often denoted as Ti*), used in varying sizes from thin wires to pieces of mesh of several cm^2. The electrodes are either directly embedded in mortar in a cavity in the concrete or prefabricated by casting in a mortar body and then embedding the whole assembly. The potential of DPs depends on the chemical nature of the electrode material and on the chemical environment, in particular pH and oxygen concentration in the adjacent concrete. The potential is considered stable only for shorter periods. Typical electrode to steel resistance varies, amongst others, with the size of the Ti* element and may lie between 1000 Ω and 100 kΩ.

All electrode potentials have a small temperature dependence. Potentials due to chemical differences (Donnan, liquid junction or diffusion potentials) tend to be less than 5 mV.

The theoretical life of electrodes is typically 30 years. In practice, cables, isolation and connections may determine their working life. An important failure factor is the electrolytic connection to the concrete. Drying out and shrinkage of the embedding mortar may cause gradual or complete loss of contact.

Testing involves potential and resistance testing. The potential of REs is measured (calibrated) at the manufacturer. After installing, potential can be tested using an external, portable cell. This is subject to errors due to local potential differences. Resistance testing must be carried out shortly after installing and repeated over time to get an impression of resistance increase due to mortar hydration. Contact loss will show up as a stronger resistance increase, usually dramatic. An occasional execution error is not removing the plastic cap of SSE or Mn/MnO_2 electrodes.

6 Long term performance of RE and DP

6.1 General

The long term performance of electrodes will be illustrated from several case studies of projects in The Netherlands and some additional observations.

6.2 Case Laan van de Vrede, Groningen

In Groningen, ICCP systems were installed on seven identical apartment buildings, one in each year during the period 1993 – 2000. Corrosion and damage had developed in the 1980s due to a moderate level of mixed-in chlorides and had been repaired, but damage reappeared in the 1990s. Each system was installed as a single zone of approximately 600 m^2 of protected concrete surface, consisting of slabs, columns and beams. The anode was a conductive coating based on an acrylate binder containing an intrinsic conductive polymer (type Ahead, from Coating A.S.). As a primary anode a silver woven band was used (type PDR). Due to specific restraints of the anode materials, the operating voltage as specified by the manufacturer was limited to 2 V. Each building contained 12 decay probes based on graphite (type Rover), installed directly in the repair mortar and distributed over slabs, beams and columns. For more details see [13].

At the time of a full system review in 2016 by the first author, all 84 DPs were still fully functional. This was verified by measuring steel potential, resistance between reference electrode and reinforcement (cathode) and response of the steel potential to an increase or decrease in applied voltage. The performance criterion of 100 mV depolarisation in 24 hours as per ISO 12696, which did not exist yet at time of installation, were generally not met. This was not due to failure in the reference electrodes, but to the restraint of 2 V maximum supply voltage, which apparently was too low, and partial failure of anode system continuity due to breaks and discontinuity in the silver primary anode. The DPs in the oldest system dated from 1993 and at the time of review had been in service for 23 years, others for 16 years or more. None of these had failed as DPs. The first system has been replaced by a new CP installation in 2021, again with a conductive coating as anode, albeit a different type. As the entire electro-technical installation was replaced and all connections were lost, it was more convenient to install new sensors. The next system will be replaced in 2022 and the other five will follow in the coming years.

6.3 Case Valkenstede, Hoogeveen

In Hoogeveen an ICCP system was installed on an apartment complex in 1995, in three zones totalling to 280 m^2 of protected surface, comprising 60 gallery slabs and 11 cantilever beams. The anode was a conductive coating based on an acrylate binder containing carbon black (type DuoDac 85, from Duochem). A copper/niobium/platinum clad wire was used as a primary anode (type Anomet 40).

Each zone contained three REs based on manganese dioxide (type ERE-20, from Force). During operation and at the time of a full system review in 2018, all 9 reference electrodes were still fully functional. This was verified as described in section 6.2. At one location, steel potentials were verified by potential mapping on the concrete surface (where the anode system was removed). The steel potentials as measured with an external copper/copper sulphate electrode (CSE) were in agreement with the measured potential of the built-in RE, within approximately 20 mV.

The performance criteria as stated in ISO 12696, which did not exist yet at time of installation, were generally not met. This was not due to failure of the REs, but due to the anode material which has been operating at an uncontrolled high voltage due to a lack of monitoring during 12 years post installation. This has led to acidification at the anode to concrete interface and local disbonding, in all elements with a high water load due to leakage.

The REs are from 1995 and at the time of review had been in service for 23 years; none failed during that time. The CP system has been scheduled for replacement including an extension to other elements that show corrosion related concrete damage, developed over the past 25 years.

6.4 Case Saffierflat and Parelflat, Groningen

In Groningen an ICCP system was installed on two identical apartment buildings in 1996/7 and 1998, respectively. Corrosion and cracking in cantilever beams were due to mixed-in chlorides at moderate levels, 0.1-0.6% by mass of cement and some carbonation. Each building comprised two zones of approximately 650 m^2 of protected surface for 559 beams per building, divided into the two zones based on façade orientation. The anodes were activated titanium ribbon mesh (type Lida Grid 20 mm, De Nora) placed in grouted longitudinal boreholes.

Each zone contained 4 DPs based on an activated titanium wire precast in a mortar cylinder. During operation and at the time of a full system review in 2016, 9 out of 16 reference electrodes were still fully functional, verified as described above. The performance criteria of ISO 12696 were generally met, but the electro technical installation, cable ducts, conduits, connection boxes and such, were starting to show signs of failure. The 7 DP failures were due to failing connections or failing cables and wiring in the electro technical installation.

The oldest reference electrodes are from 1996 and at the time of review had been in service for 19 years. The first system has been renovated by full replacement of the electro technical installation, while reusing the installed anodes. New anode connections were made and steel connections were checked and reused or replaced as needed. The 16 original DPs are still in use, but two additional DPs were installed for each zone. The second system is scheduled for renovation in the first half of 2022.

6.5 Case Mozartlaan and Bachlaan, Tilburg

In Tilburg, ICCP was installed on two identical apartment buildings in 1990 [21]. Cantilever beams showed corrosion and cracking due to mixed-in chlorides. Each building had 68 zones installed of approximately 25 m^2 of concrete surface each. The concrete protected consists of 1224 beams per building, with 18 beams per zone. The anodes were profiled activated titanium ribbon mesh strips (30 mm wide, Heraeus) in boreholes along the length of the beams. A reinforcement contact was made in every single beam, because of poor continuity between beams.

Half of the zones contained a single RE, i.e. a total of 34 per building, based on MnO_2 (Force). As half the zones did not contain an RE, these zones were operated at a predefined current supply based on the performance of zones with an RE. This type of operation and control is now unusual and zones would now be larger. During operation a steadily decreasing number of reference electrodes was deemed ‘functional’.

At the time of a full system review in 2020, approximately 35% of the REs were still fully functional, verified as described above. The performance criterion of 100 mV depolarisation in 24 hours, as per ISO 12696, was not met. This has been identified as due to failure in the electro technical installation, cable ducts, conduits, connection boxes and such. Furthermore, a large portion, approximately 50%, of steel contacts in the beams were failing and showed discontinuity. It is likely that many RE failures can be contributed to the failing connection to the steel in those particular beams. This was incidentally observed, but not verified in all cases.

The reference electrodes are from 1990 and at the time of review had been in service for 30 years. The first system has been renovated in 2021 by full replacement of the electro technical installation, while reusing the installed anodes. New anode connections were made and all beams were connected using new steel connections. The original REs were discarded and new reference electrodes were installed. In the new installation, a total number of 34 zones has been realised, containing a total of 136 REs. During installation, 3% of those newly installed reference electrodes failed the quality check (4 pieces) and have been replaced. Failure during installation has been identified as due to inappropriate application of REs and embedding mortar. All failing REs were installed by the same team in the same period and not removing electrode caps was the main cause of these failures.

6.6 Case Liggerkoppen, Oost Nederland

ICCP was installed on parts of 30 bridges of similar build up with prefabricated post-tensioned deck girders; for more background and details see [22]. Many beam heads had developed corrosion and spalling due to de-icing salt leakage of overlying expansion joints. Based on existing damage, 1300 beam heads were protected in 2013-2014. ICCP was applied with a conductive coating (without top coat) on beam heads over about 1 m length. Two sensors were placed in every protected beam head, one DP at the outer steel (for depolarisation testing) and one RE (SSE) near the post-tensioning anchors (for monitoring the absolute potential). Three beams formed one zone with a total protected surface of about 3 m^2 of concrete surface fed by one small local power unit that included the monitoring circuitry for the six sensors in each zone.

A total of 1890 titanium DPs at the depth of the outer reinforcing steel and 1890 SSE REs at the depth of the posttensioning anchors (>100 mm) were installed. During installation, 14 sensors were found not to work properly and were replaced. In the subsequent nine years, 30 sensors failed; 18 DPs and 6 REs without a clear cause of their failure, all in different zones; and all sensors (3 DPs and 3 REs) stopped working in one zone due to electronics failure. The failure rate during installation was 0.5%, and during a 9-year service less than 1%.

6.7 Other cases

In a large recent case with titanium ribbon mesh anodes in a cementitious overlay, 535 potential sensors were installed, 401 titanium DPs and 134 SSE REs. During installation, only 3 failed, c. 0.5%. During the first two years 8 failed (<2%) due to subsequent works, in particular drilling of anchors in the overlay. The number of remaining sensors was large enough to ignore the failing electrodes.

A previous study [15] showed that in five out of 50 cases of systems of ten-year age or older, at least some of the REs or DPs had to be replaced.

7 Discussion

Field experience shows that the general failure rate of potential sensors (REs or DPs) is low, up to at most a few percent of the installed numbers. In several cases mentioned, all sensors kept working for more than 20 years, both REs and DPs. The occurrence of failure can be distinguished between during installation and during service. Failures during installation can be due to improper placing, e.g. incomplete filling of the cavity with mortar, or to not removing the plastic cap from an electrode. These failures should be detected by testing during execution and can be corrected easily. If a failure is detected during commissioning of the CP system, correction is still possible, but may require more work if scaffolding has already been removed. Failure during service can be due to contact loss of the electrode, usually due to drying out of the concrete or the placing mortar, or due to damage to cables and connections, either mechanical or due to leakage into junction boxes. Such failures can be detected during monitoring tests, typically twice per year. Replacement is usually costly, in particular when access is difficult.

Despite overall low failure rates, failure of a single sensor in a zone with only two sensors significantly reduces the controllability of that zone. Following the rules for numbers of sensors, a zone with two sensors can be as large as 200 m^2, in which case one sensor is clearly insufficient. For small zones, failure of single electrodes can be less of a problem. In any case, installing a few more sensors than strictly needed can be a good strategy to optimise long term controllability and cost. Protecting cables and junction boxes from mechanical damage including vandalism and leakage can be just as important.

8 Overview and conclusions

Cathodic protection reduces corrosion by depressing the steel potential. In concrete, a negative shift of a few hundred millivolt is sufficient to reduce the corrosion rate to insignificant values, essentially independent of chloride levels or carbonation. Effective working lives of ICCP systems may be as long as twenty years and more, without significant maintenance being needed. Regular monitoring is required, however. Sensors for measuring the potential are critical elements of every monitoring system. Generic types of potential sensors are true reference electrodes and decay probes. True reference electrodes are based on a known, stable redox reaction, produced by specialised manufacturers, with a relatively high price. Decay probes can be simple pieces of metal, usually activated titanium of a type that is also used for anodes. They are either installed directly in a cavity in the concrete that is filled with repair mortar, or precast in a mortar cylinder that is subsequently placed in a cavity with repair mortar.

True reference electrodes and potential decay probes have been found in many cases to be able to work properly for decades. For testing the quality of protection of reinforcing steel using the 100-mV depolarisation criterion both generic types are equally suitable. However, true reference electrodes with their stable long-term potential are necessary to assess the potential of prestressing elements, either post-tensioning ducts and anchors or pretensioning strands and cables.

Failures of electrodes have occurred, although typically at low rates of a few percent of the installed numbers, both during installation and during service. Failures during installation should be detected as part of quality testing during installing a CP system and can be easily corrected by placing new electrodes. Failures during service should be detected as part of monitoring activities, usually twice per year. Installing new sensors can be costly.

Usually a small number of electrodes is installed per separate protection zone. Installing a few more sensors than strictly necessary according to the rules can be economically advantageous in the long run and can benefit the overall controllability of protection quality.

Proper installation of REs and DPs and protecting cables and connections are essential to obtain good long-term performance of cathodic protection of concrete structures.

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