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Cathodic protection of steel in concrete – experience and overview of 30 years application

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Abstract. This paper presents an overview of 30 years' experience with cathodic protection of steel in concrete in The Netherlands. Principles and practical aspects of CP and its design and installation are presented. Three phases have passed from the late 1980s until present: pioneering, development and maturity. In the first period CP was mainly applied to precast elements corroding due to mixed-in chlorides. The parties involved worked together to draw up a Technical Guideline. In the second period, application to bridges came up, including post-tensioned structures, which was then innovative. Furthermore, galvanic anode systems were introduced. In the third period, CP became a fully accepted method of securing durability and safety. Renewed collaboration led to a database that allowed analysis of various aspects of CP system working life, including shortcomings in early systems. Major successes and lessons learned will be presented. Technical and non-technical developments are highlighted and some recent innovative CP components and systems are discussed.

1 Introduction

Increasing numbers of concrete structures develop corrosion of the embedded reinforcement. This is due to prolonged exposure to aggressive influences including chlorides from sea water and de-icing salts or to the effects of mixed-in chlorides; both cases are aggravated by carbonation [1, 2]. Many older structures are more sensitive due to lower cover depths and lower concrete quality than what is common nowadays. Reinforcement corrosion causes cracking and spalling of concrete and steel cross section loss, which compromise serviceability and eventually structural safety. Consequently, repairing and protecting concrete structures has become a substantial industry over the past 30 years. However, in many cases conventional methods of concrete repair have been found not to be effective or durable [3, 4]. Cathodic protection (CP) on the other hand, has demonstrated to be an effective and durable method for protecting steel in concrete. This paper addresses some of the history and experience with CP of concrete structures, based on the authors' involvement in The Netherlands and documentation from other sources.

CP of concrete 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. Various types of anode, including cast iron and cokes in asphalt and slotted systems with various mortars, were applied with varying results; most of these early anode types have been discontinued [7]. Subsequently, new anode materials became available, in particular activated titanium and conductive coatings, versions of which are still widely used today; galvanic anodes were introduced in the late 1990s. From about 1985 the UK [6], Italy [8], Norway [9, 10], Denmark, Switzerland [11, 12] and The Netherlands [13] saw increasing application of CP to concrete. More recently in Germany, France, Belgium and Switzerland increasing numbers of systems are being installed. Long term performance results and an overview of necessary interventions of large numbers of systems have been published [14, 15].

2 Principles

Reinforcing and prestressing carbon steel in concrete are normally passivated due to the high alkalinity in the pore solution, brought about by dissolved potassium and sodium hydroxides and buffered by solid calcium hydroxide, at pH values above 13. Under passivation, corrosion is negligible and very low rates of oxidation and reduction take place. In aerated concrete potentials of about +0 to -100 mV versus a saturated calomel electrode (SCE) are established. Lowering of the pH due to carbonation, the reaction with carbon dioxide from the atmosphere, or the presence of chloride ions above a certain threshold concentration cause depassivation. Upon corrosion initiation anodic (oxidation) reactions and cathodic (reduction) reactions are strongly

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accelerated compared to the passive state, which can be described by the following equations:

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

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

With chloride induced attack localised or pitting corrosion 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 regions and strong potential gradients develop between anodic and cathodic regions.

The principle of cathodic protection is shifting the potential of the steel surface to more negative values, slowing down oxidation reactions (eq.1) and accelerating reduction reactions (eq.2). In concrete, shifts of a few hundred millivolts suffice to return corrosion rates to negligible levels [8]. This is due to positive effects of the current: increased cathodic reactions produce hydroxyl ions and increase the pH at the steel/concrete interface; the negative charge of the steel repels (negatively charged) chloride ions. The potential shift is brought about by a current flow from the concrete into the steel; this current is fed into the concrete from an electrode that has to be installed on the concrete surface or in the cross section, called the anode. At this anode, oxidation reactions take place that consume hydroxyl ions or that oxidise materials at the anode/concrete interface according to the following equations:

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

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

The former reaction may cause acidification such that loss of anode/concrete bond may occur; the latter corrodes galvanic anode materials or causes degradation of carbon particles in conductive coatings. Possible side effects at the cathode are alkali accumulation due to ionic migration and hydrogen evolution due to the following cathodic reaction:

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

. Hydrogen evolution at the steel surface may cause embrittlement of prestressing steel; this reaction can be avoided by limiting the current density at the prestressing (or duct) surface. As reaction (5) only occurs at very negative potentials, typically -1100 mV versus SCE, monitoring the steel potential can be used as a safeguard. At more positive potentials, only reaction (2) is possible and hydrogen evolution is excluded. High alkali levels may provoke alkali-silica reaction if reactive aggregates are present. Both of these adverse side effects occur only at relatively high current densities. For more information on principles and effects the reader is referred to [1]. All reinforcing steel and other metals embedded in the concrete has to be continuous and connected to the cathode circuit; otherwise it will not be protected or may even develop accelerated corrosion due to stray current effects.

3 Practical aspects

Two basic types of CP systems exist: impressed current CP (ICCP) and galvanic or sacrificial CP (GCP). The main components for both are illustrated in Figure 1. With ICCP a low voltage DC power source causes the current to flow. The anode consists of a material that is not or only slowly consumed, such as activated titanium (whose surface is covered with noble metal oxides, Mixed Metal Oxide or MMO) or a conductive coating. Activated titanium has the shape of a mesh embedded in a cementitious overlay installed on the concrete surface; or of strips in boreholes in the cross section or in slots cut in the concrete surface; holes and slots are filled with cementitious grout. Conductive coatings are carbon filled polymers applied to the concrete surface, usually covered with a top coat. Primary anodes are metal wires used to feed the current into the actual anode material; they should be separated closely enough to avoid large potential drops in the metallic circuit. Cementitious overlays and conductive coatings should be durably bonded to the concrete surface to ensure electrical contact. Obtaining good bond requires adequate surface preparation; proper application and curing are critical. Power source and anode are metallically connected by isolated copper cables and anode-cable connections. Cable cross sections should be large enough to limit potential drops. Cables need to be redundant in order to avoid system failure due to cable interruptions (e.g. by vandalism); at least two cables should feed both anodes and cathodes, with their connections as far apart as possible within a zone. Power sources are fed from the grid or by solar or wind energy, backed up by batteries.

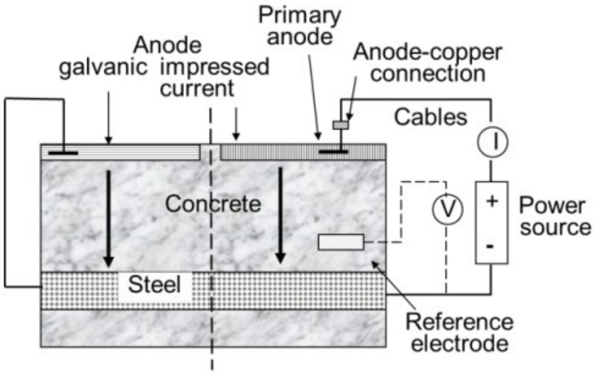

Fig. 1. Main components of galvanic (left) and impressed current (right) CP systems.

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

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

A GCP system can be built up of zinc sheet with an appropriate activator and a conductive adhesive on the concrete surface; or by embedding zinc probes with an 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 by metallic wires.

A CP system can be divided in multiple zones (separately controlled parts), if current densities between different parts of the structure are expected to be different or for practical reasons. Current densities are influenced by differences in concrete electrical resistivity due to differences in e.g. exposure to precipitation or concrete composition [13, 18]. Practical reasons can be avoiding large zones with poor controllability or a low capacity of available power units. Basic design of CP is based on a steel 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 complete concrete cross section or only the steel closest to the surface. In the longer term, most CP systems operate at much lower current densities, typically of 1 – 5 mA/m^2 (steel surface). It should be realised that the current density per unit of concrete surface area can be quite different. Buildings usually have less than 1 m^2 of steel surface per m^2 of concrete surface; the steel/concrete density of engineering structures like bridges can be substantially higher, in particular in areas with higher stresses. In practice, impressed CP current is kept as low as possible by applying a low voltage to slow down system degradation and to limit negative side effects, while maintaining sufficient protection. In galvanic systems, the current cannot be externally controlled and the zinc consumption rate is a function of concrete resistivity and steel density, which will determine their working life.

Preventive application 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 spread is more favourable.

Protection quality control is performed by interrupting the current for several hours to one day or more and monitoring the steel potential using a reference electrode (RE). For ICCP, the current is switched off at the power source. For GCP, usually a special section is made that allows switching off; in the majority of such a system the anode is directly connected to the steel at multiple spots. Due to interrupting the current, the steel potential moves to more positive values. This test is called depolarisation test. A steel potential depolarisation (shift) of at least 100 mV between instant off (which eliminates ohmic drop) and up to 24 hours is the most widely used criterion for sufficient protection [19]. Several RE's should be embedded at representative spots in each zone. Regular monitoring, with depolarisation testing at least twice per year and a visual inspection once a year, should be warranted by a maintenance contract, usually between the owner and the company that installed the system. Increasing numbers of systems are remotely monitored or controlled using dataloggers and modern wireless connection technology.

4 Experience

As mentioned, CP application began in Europe around 1985 in the UK and Italy. The first concrete CP system in The Netherlands was installed in 1986/7 on a cycle lane of a bridge, the Stadium Viaduct in Rotterdam [13]. It protected 150 m^2 of concrete in two zones; the anode consisted of carbon filled polymer cables with a copper wire core in a cementitious overlay. Subsequently, a few projects were made with this anode that later was taken off the market. In 1989 activated titanium anodes were introduced; titanium wires were installed in precast concrete facade elements with corrosion due to penetrated chloride from sea water mist. In 1990 titanium strips were placed in holes drilled longitudinally in 2500 precast cantilever beams with mixed-in chloride, supporting galleries and balconies in two apartment buildings in Tilburg. Current distribution within the cross section was studied in the laboratory; and between beams in the field [20]. Internal cover measurement was used to avoid anodes and steel to being too close or even short-circuited; a distance of 15 mm was thought to be a good minimum. In locations where the steel was found being too close to the borehole, a polymer isolation tube was placed around the titanium strip. Two similar projects were made in Groningen in 1997 and 1998 (1000 cantilever beams) with drilled in titanium strip anodes; and with a conductive coating on the top floor (beams and roof slab). Carbon based conductive coatings were introduced as anode material and were applied to several buildings with mixed-in chloride. A series of seven buildings with columns, beams and slabs with mixed-in chloride and moderate concrete quality were protected with a conductive coating between 1993 and 2000 [13]. For long term performance of some of these early systems, see below.

It appeared that the durability and repair of precast concrete with mixed-in chloride was a major problem in the country. Conventional repair was found not to be effective: in many cases corrosion and concrete cracking reappeared within a few years after such repairs. On the other hand, CP showed to be effective and durable.

Considering that uniform current distribution was important and would be mainly determined by the electrical resistivity of the concrete, it was felt that the resistivity of materials used for repairs associated with CP should be similar to that of the parent concrete. This notion was adopted by the European Standard on CP of concrete [19]. Exposure to precipitation and solar radiation, e.g. due to orientation of facades, was also considered as having an effect on resistivity and was used to separate systems into multiple zones.

CP companies and knowledge institutes worked together to draw up a CUR Recommendation published in 1996 [21]. It addressed curative application to reinforced concrete and had the character of a guideline including technical considerations and limiting values. Between 1987 and 1995 CP was installed on a total of 16 structures, mainly buildings with mixed-in chloride, either with activated titanium anode strips in boreholes or with conductive coatings on the concrete surface. This period can be said to be the pioneering period of CP in The Netherlands.

In the following period, roughly 1996-2004, application of CP on bridges and other infrastructure developed. In one project, corrosion had induced widespread delamination in a thick wall of a basement of a bridge. Using titanium mesh and shotcrete was rejected due to the risk of the delaminations hindering current flow to the reinforcement. Subsequently a system based on drilled-in titanium strip anodes was designed and installed. However, reinforcing bars appeared not to be positioned at regular intervals as was expected when making the design, and many additional holes had to be drilled to avoid short circuits between anode strips and reinforcing bars. Also in this case, steel continuity was largely absent, such that all rebars had to be connected. To avoid these issues, the preliminary investigation should have looked more carefully for the location of steel bars and for steel continuity.

In another bridge corrosion had developed in the edge beam of the deck above the abutments, adjacent to joints that were leaking de-icing salt solution. Previous repairs had failed. Making better repairs would have required lifting the deck and taking the bridge out of traffic. CP was chosen as a more user-friendly solution. The complication was that the deck was post-tensioned and concern existed for overprotection, causing hydrogen evolution and possibly hydrogen embrittlement of the prestressing steel (see above). The problem was addressed by consulting Pietro Pedeferri, who made clear that monitoring the potential of the prestressing steel ducts and maintaining it above a safe absolute potential value of -900 mV versus SCE would exclude hydrogen evolution [8]. This includes a substantial safety margin compared to potentials where hydrogen evolution would really occur (typically -1100 mV), see above. Subsequently CP was installed using a conductive coating; monitoring the potentials around prestressing ducts and anchors showed them to be well in the safe region. This approach and the safe value for the absolute potential were later adopted in the European Standard EN 12696, that was published in 2000 [19]. In addition to allowing CP of prestressed concrete, this Standard also included preventive application, Cathodic Prevention (CPre), which had been introduced by Pedeferri [8]. The Standard had a performance based approach, rather than being a technical guideline.

Around 2000 galvanic anodes were introduced for CP in concrete, based on the sacrificial action of zinc. Zinc sheet with an ion conductive adhesive was applied to various buildings and bridges.

Between 1997 and 2004 a total of 79 structures were provided with CP, comprised of buildings with mixed-in or penetrated chloride, bridges and parking structures exposed to de-icing salts and swimming pools. In some cases a single structure contained more than one CP system, e.g. one on the facades and one on a basement floor.

By 2004, CP had become a well-accepted method for effective long term protection of concrete structures with corrosion damage. Involved companies, although relatively small and with economic ups and downs, joined in sponsoring a collective research project by TNO. It included setting up a database of CP systems in the country and further development of numerical models for CP [22]. The database was updated twice. Ultimo 2010, a total of 150 concrete structures in The Netherlands had CP installed, comprised of 105 buildings (apartment blocks, offices, parking and industrial buildings) and 45 bridges and other infrastructure, with a total of 85,000 square meters of protected concrete surface [15]. These numbers do not include 65,000 m^2 of ground floor elements with mixed-in chloride provided with CP.

Out of 150 CP systems, 65 had conductive coating anodes, 50 activated titanium and 35 galvanic anodes. For 105 systems good documentation was provided, usually by the company that installed it and carried out maintenance. 50 documented cases had been operating for ten years or more and 55 cases for less than ten years. The remaining 45 cases were not documented and/or not monitored, which included most of the galvanic systems.

The survey and subsequent analysis showed a mixed picture of an overall low rate of system degradation and some weak details [15]. Weak details included accelerated corrosion of poorly insulated anode-copper connections; and some cases of degradation of primary anodes in conductive coating systems, in particular in older ones. It appears that primary anodes should be made of truly inert materials, e.g. noble metals like platinum; less resistant materials are prone to degradation over the years. Some cases of power unit of reference electrode failure were noted. Over time, CP companies improved these weak points, as was borne out by later systems. Very low numbers of overall anode degradation were found. However, local degradation of conductive coatings due to water leakage from overlying parts was an important cause of the need for (some cases of) maintenance. Conductive coating anodes on buildings with relatively sheltered facades may last as long as 15 to 20 years. This is shown by the seven buildings mentioned above. By 2013, so 13 to 20 years after installation, these systems did not comply to the depolarisation criterion anymore and were in need of maintenance. However, corrosion or concrete damage were completely absent. Another project with drilled in titanium strip anodes and conductive coating on the top floor showed good performance of the titanium system after 17 years; and significant degradation of the conductive coating part. Activated titanium systems perform well over at least 20-25 years in many well-documented cases; working lives of 25 and more years appear very well possible. This experience is in agreement with a recent study on long term performance of CP systems on motorway structures [14], which showed that conductive coating anodes may work for a very long time, also in infrastructural works and despite visible deterioration of the coating.

5 Market and recent developments

In early 2015 the database on CP systems was updated. An overview is presented here. By the end of 2014, a total of 230 structures had CP with some multiple systems installed, counting a total of 250 CP systems. Figure 2 presents annual and cumulative numbers. They comprised 105 buildings, 97 bridges and 44 other structures. From the total, 103 had conductive coating anodes, 57 titanium and 58 galvanic anodes (29 had other anodes or two types). Owners were The Ministry of Infrastructure (65 systems), lower governments (41) housing companies (48), private collective building owners (24) and other owners (69). Increasing numbers of projects involved protecting corroding bridge abutments, preventive applications and systems with ground bed anodes; some are illustrated in more detail below.

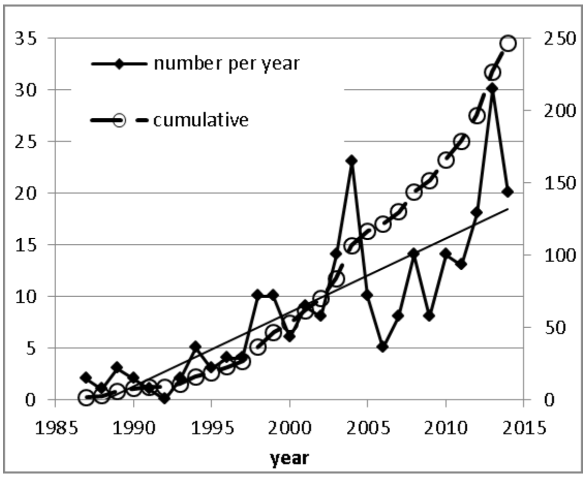

Fig.2. Number of CP systems installed in The Netherlands per year (left Y-axis), cumulative number (right Y-axis) and trend line for number per year.

CP was installed in 30 bridges of similar build up with prefabricated post-tensioned deck girders; for more considerations and details see [23]. Many beam heads had developed corrosion and spalling due to leakage of overlying expansion joints. Based on existing damage, 1300 beam heads were protected in 2013-2014. This involved applying CP with a conductive coating (without top coat) on beam heads with damage and (undamaged) adjacent ones, about one-third of the total number. Two RE's were placed in every beam head with CP, one at the outer steel (for depolarisation testing) and one near the post-tensioning anchors (for monitoring the absolute potential). Subsequent operation showed that absolute prestressing potentials were well on the safe side of the -900 mV criterion. A maintenance contract for 20 years was agreed, including visual inspection of the non-protected beam heads. In 2017 many unprotected elements were found to show corrosion and damage; apparently they contained chloride levels that had previously not caused corrosion damage, but they had four years later. Subsequently CP will be installed on those elements.

For a series of new bridges in a motorway around the city of Groningen, corrosion in the abutments would be highly undesired for the effects of repair activities on traffic flow. Consequently, cathodic prevention was installed. The anodes were titanium strips cast in mortar blocks that were placed between rebar cages and concreted when casting the abutments. Similar anode blocks were placed inside precast deck beams. Because of the preventive principle, monitoring could be kept at a low level (automated checking current flow, long interval depolarisation testing). Four bridges of this type were provided with CPre in 2012/13, and several more are planned for 2018.

In recent years, more and more systems are based on anodes in the ground surrounding wall-type structures such as locks and tunnel walls. One example concerns a two-tube tunnel with walls built of ground mixed with cement. Concerns for cracking and durability resulted in installing CPre, with current being provided from anodes placed in the ground on either side of the walls. Numerical modelling based on ground and "concrete" resistivity was applied to calculate adequate anode-to-anode distances while considering anode-to-wall distances allowed by the right-of-way around the tunnel. After installation and commissioning, several anodes were found to have stopped working due to later works in the area, damaging anode cables. This is a concern for systems with ground anodes.

Based on increased communication between CP companies, research institutes and consultants, a CP-knowledge centre was founded to promote application of CP. It addresses technical and non-technical issues. For example, a working group suggested to set up a course for teaching technicians at level 2 of the European certification system [24], which started in 2016. Another group proposed an approach to service life prediction of galvanic anodes, based on experience with current densities in practice and Faraday's law. The benefit is that all parties have a common basis for offering galvanic systems for a particular working life.

After 30 years, the "second life" of CP systems can be considered. In particular older conductive coating systems may approach the end of their working lives. This poses the question how sustained corrosion protection should be achieved. Obviously, installing a new CP system is one way. However, such a system can be designed less conservative, supposing that corrosion has not already re-activated. Some information exists on residual protection after stopping the current flow [25], although the positive effects were documented after short term CP operation. In any case, this matter deserves attention from both research and CP engineering communities.

Another long term issue is that the accumulated cost of monitoring CP systems may be substantial [26]. If it can be shown that after some time of CP operation re-activation of corrosion takes longer or is improbable, increasing the monitoring intervals of systems that have operated well for several years should be considered. Visual inspection remains necessary, but the interval could be increased if remote monitoring is used to guarantee current flow.

6 Overview and conclusions

In The Netherlands CP of concrete structures has seen many successful applications and considerable growth, from a few to more than 20 systems being installed per year over the past 30 years. Many different types of systems have been developed, installed and maintained and lessons have been learned. Preliminary investigation should be thorough and must, among others, establish reinforcement positioning and steel continuity. Corrosion due to mixed-in chloride can be effectively stopped with CP, which is hardly possible with conventional repair. Post-tensioned structures can be protected without the risk of damaging prestressing steel, provided a proper design is made and absolute prestressing/duct potentials are monitored. Degradation of components has occurred, but sensitive details are well-known and have been improved. Overall good working lives have been documented for many systems based on long-term field experience. Conductive coatings can remain effective for up to and above 15 years. Activated titanium systems have worked for 25 years and more. Galvanic systems provide a possibility to operate independent of power being available; an approach to predict their working life has been proposed. Installing CP on bridge joints with corrosion due to de-icing salt leakage is effective and efficient. The preventive application of CP is increasing.

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