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Cathodic protection of concrete with conductive coating anodes: 25 years of experience with projects and monitoring results

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Abstract. An overview of projects with CP systems in the Netherlands is given, where during a period of 25 years conductive coating was used as an anode. Projects on bridges, viaducts, power plants, apartment and industrial buildings will be presented, with reinforced and pre-stressed concrete, and with the protected elements varying from floors to balconies, beams to abutments and cantilevers to columns. All being monitored for up to 25 years and now presented in one overview showing the possibilities of the application of these types of anode, as well as the thresholds. Measurements on a variety of constructions were carried out during 25 years and show interesting results, enlarging the knowledge on CP with conductive coatings as an anode and the effectiveness of this type of CP systems and its development in time, as determined by the depolarisation values of the system and (protective) current densities. From these measurements conclusions can be drawn and lessons can be learned regarding the use, design, installation and effectiveness of CP systems with conductive coatings as an anode.

1 Cathodic Protection of concrete

Due to chloride contamination of concrete a large amount of constructions worldwide suffer from damage caused by corrosion of the steel reinforcement. Often in those cases traditional repair is not suitable for achieving a durable repair and an extended service life of the construction. An appropriate way to meet the requirements of the owner is to apply cathodic protection (CP) on the parts of the construction with chloride damage and/or contamination. [1]

CP as a protective maintenance measure is well developed, and is one of the fundamental principles applied for maintaining concrete constructions and extending service life. As such it has become part of the European Standard involved in concrete maintenance, EN1504. [2]

By applying CP on a concrete construction the applied DC voltage and accompanying protective current, stops corrosion and facilitates (re)passivation of the steel in the protected parts. [3]

The design, application and monitoring of CP is governed by the standard EN12696 [4], which gives guidelines for the criteria for design and evaluation of performance, mostly by performing depolarisation measurements during the service life of the protective system. Applied voltage, protective current and measured depolarisation (over 24 hours) values at the protected steel are considered the most important indicators of performance over time.

Over the years applications of CP on concrete in The Netherlands, have evolved to more frequent and smaller applications on various concrete constructions. [5] The early experiences were captured and gathered, resulting in a recommended practice in 1996, the CUR-Aanbeveling 45. [6] As of 2000 the international experiences were used to establish an international standard EN12696, which was by the current version of 2016 adopted as ISO standard. These guidelines and standards helped to mature the concept of CP to a mainstream maintenance tool in The Netherlands.

At the same time, market developments were accompanied by technical developments in the materials and systems used for CP. Besides developments in electronics, data acquisition and communication, reference electrodes and other major parts of the CP systems, the most significant change was the ongoing development in anode materials used for the anode systems in contact with the concrete.

2 Conductive coatings as an anode in The Netherlands 1989-2018

As of 1989 CP systems in The Netherlands have been installed where the anode system was applied as a conductive coating. In this study, various CP projects have been evaluated in which at least one of the authors was involved in the monitoring phase of the installations. In general, involvement was wider going from preliminary assessment of concrete damages, design of CP systems,

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supply of materials, execution of the installation works, quality control, commissioning, maintenance on CP installations and even decommissioning of installations at the end of the service life.

A total number of 108 CP installations in The Netherlands is evaluated, where the anode system was based on a conductive coating. At present 85 installations (79%) are still active, 5 installations (5%) were decommissioned at the end of the constructions service life, and 18 installations (17%) failed in some significant way during the service life.

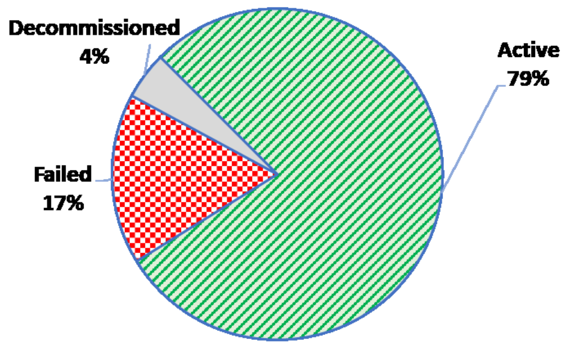

Fig. 1. Status (2018) of 108 CP installations with CC

The CP installations were mostly applied on apartment complexes (47%) with typical elements as slabs and cantilever beams, on infrastructural works like bridges and viaducts (39%) with typical elements as abutments, prestressed beams, columns and walls, and to a lesser extent on swimming pools (6%), office buildings (4%), parking garages (3%) and industrial constructions (2%). Normally these installations are grid powered, but in 26% of the installations solar panels were used.

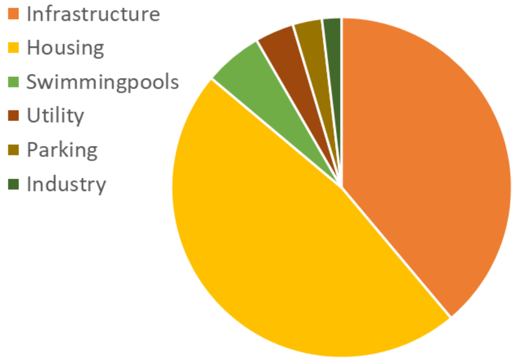

Fig. 2. CP installations by structure usage type

The concrete constructions protected were mostly common reinforced concrete (67%), and in 33% of the projects the protected concrete was built with prestressed steel, with bonding in all cases. In those prestressed constructions the purpose of the CP installation was in general to protect the ordinary steel in the outer shell of the concrete, and if needed all together, the protection of the prestressing steel tendons or rods was considered secondary. Almost all CP installations are installed on CEM I based concrete constructions although some installations were used on CEM III concrete constructions. It is estimated that the CEM III construction parts are about only 10% of the total, but there is uncertainty in this assessment as the cement type of the construction to be protected, is not always documented (or assessed) in CP projects.

The 108 CP installations total a protected concrete surface of 50.035 m^2. The average CP installation is therefore 463 m^2, but as a small number of very large projects can influence this numerical average, it is noted that the median is 245 m^2. In the same sense the average service life of the installations at present is 10,6 years while the median is 8,9 years (and the oldest still functional CP system with the original anode is 22 years old).

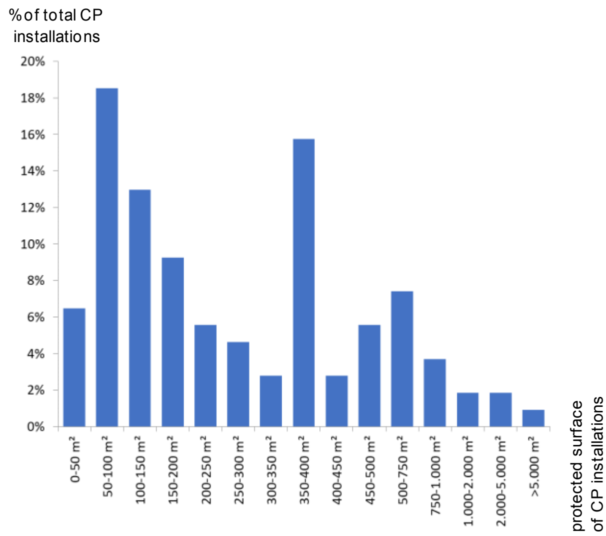

Fig. 3. CP installations distribution in size of protected surface

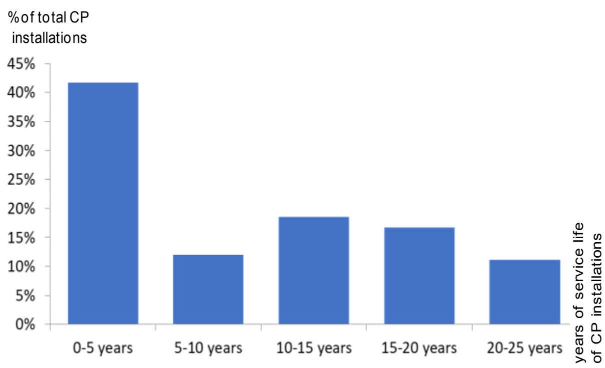

Fig. 4. CP installations distribution in years of service life

3 Conductive coating binder and primary anode

The conductive coatings used as anodes, varied on both binder technology, and on the conductive material incorporated in order to obtain the high conductivity needed for application as a CP anode.

Most coatings are traditionally based on acrylic binders, but over time developments were made to use a mineral silicate binder as an alternative. In time the dominant binder technology in The Netherlands, shifted from acrylic to silicates.

In most conductive coatings (CC) graphite is used as the electrically conductive phase, although historically there have been a number of applications based on an intrinsically conductive polymer which is no longer available in the market as an anode system. The graphite phase used as conductive filler, varies from industrial carbon black powder, to natural graphite powder, to carbon fibres with a nickel coating.

These combinations of binder and conductive filler have led to the subsequent usage of:

- An acrylic, carbon black based coating from MatCor: 2 installations (2% of the total), installed on average 26 years ago, for which both installations are now deemed failed after a service life from 10-15 years. Failure is induced by leakages of water on/in to the concrete.
- An acrylic, carbon black based coating from Corrosion Services (DuoDac 85): 2 installations (2% of the total), installed on average 23 years ago, for which 1 is decommissioned within its anode service life and the other 1 is still active but now at the end of its service life after 20 years. It is noted that the anode is operating at an increasingly higher applied voltage (to well above 8 VDC) after 10 years of service life indicating 'aging' of the anode material.
- An acrylic, intrinsically conductive polymer based coating from Coatings International (Ahead): 14 installations (13% of the total), installed on average 20 years ago, for which 12 installations (86%) are now deemed failed after a service life from 1-20 years. Failure induced by failing to comply to depolarisation criteria under the material intrinsic restraint of maximum applied voltage (2 VDC max allowed). 2 installations, although operating at a higher than allowed voltage (4-5 VDC) are still functional after 21-22 years but have reached the end of their service life.
- An acrylic, nickel coated carbon fibres based coating from Basf (CP30): 13 installations (12% of the total), installed on average 20 years ago, for which 3 are decommissioned (23%) within the anode service life, 2 installations (15%) are now deemed failed after a service life from 10-15 years, and the other 8 installations (62%) are still active after 15-20 years of service life. One failure is acknowledged to be induced by leakages of water on/in to the concrete, and the other one due to failure of the electro technical installation (power supplies).
- An aluminosilicate, graphite based coating from CAS (CAS T^{3+}): 77 installations (71% of the total), installed on average 7 years ago, for which 1 is decommissioned within its anode service life and 2 installations are now deemed failed after a service life from 10-12 years, and the other 74 installations (96%) are still active after 1-16 years of service life. Both failures are acknowledged to be induced by leakages of water on/in to the concrete.

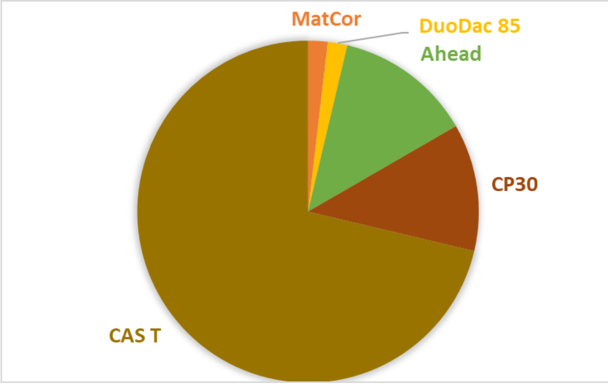

Fig. 5. CP installations distribution in CC used

Applying a conductive coating as an anode in a CP system will require the usage of a primary anode as a means of feeding the anode coating and providing an even current distribution within the length and width of the anode along the lines of the primary anodes (providing paths of low resistance in the anode system). As such the primary anode is of importance of achieving good and evenly spread performance of the anode. Although the primary anode is not formally part of the conductive coating, its significant influence on the anode performance, makes it necessary to consider the used materials. In the projects concerned the used primary anodes vary from the dominant platina clad copper wire (65% of the total; CuNbPt-wire), silver band used in the Ahead-system (13% of the total; Ag-band), nickel tape (1% of the total; Ni-tape), stainless steel tape (5% of the total; FeCr-tape), lead tape (14% of the total; Pb-tape), activated titanium wire or strip (2% of the total; Ti*), and titanium clad copper band (1% of the total; CuTi).

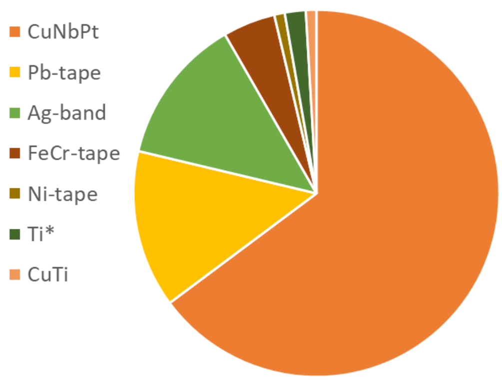

Fig. 6. CP installations distribution in primary anode used

It is noted that all but one (4 out of 5) of the stainless steel tape installations showed failure of the system, where the failure is related to the primary anode (debonding of the tape and also heavily corroding in some installations). These tapes were replaced during maintenance operations after 1-4 years of service life by platina clad copper wire primary anodes (increasing their percentage to approximately 70%). The last installation which still is active with the stainless steel tape has visual defects in form of black stains in the top coat on the primary anode. Although, still being functional, the one installation with nickel tape shows the same visual defects, i.e. black stains on the primary anode visible through the top coat.

The 14 projects with silver band were all associated with the Ahead coating system. These primary anodes also show black staining on the primary anode, but in general these stains do not show up before 8-10 years of service life. Along with these visual defects, in some installations the woven silver band showed problematic current distribution, and even full failure, on sharp bends and corners of the protected concrete where the primary anode was extended over these sharp edges.

The 15 installations with lead tape are fully functional, but one installation had some need for maintenance at localised areas where water with a high chloride content leaked directly on the primary anode. At these spots the dissolvement of the lead after formation of lead-chlorides was detrimental to the local function of the primary anode. In general the lead tapes don't show signs of oxidation, besides being probably unaffected by oxidation as lead-oxides tend to be electrically conductive (with an even lower resistivity than the lead itself).

The 3 installations with some form of titanium primary anode, show no sign of ageing or failure due to the primary anode.

The 70 projects with platina clad cupper wire as a primary anode, in general work fine. There have not been significant failures or maintenance works with regard to the primary anodes, on these projects. The only common visual defect which is observed, are pinpoint size green stains due to the oxidation of cupper at cuts and bends in the primary anode where the cupper core gets exposed as an anode. This is mostly observed at cutting edges of the primary anode, or in cases where the outer layers of platina-niobium are damaged by the usage of power equipment (drills) or iron hammers (used for fixation of the wire with the commonly used polymer pine tree plugs) on the wire. These visual defects have not led to failure in the protective CP functionality, but have been retouched in a number of installations in order to meet visual demands in some installations.

In general, in all installations the voltage drop in the anode system was relatively low. As set in the standards, this voltage drop should preferably not exceed the 10% of the total applied system voltage. As this voltage tends to be 2-5 VDC, this drop should not exceed the 200-500 mV DC. In general, if the DFT (dry film thickness) of the conductive coating is sufficient, this voltage drop will not exceed the 100-250 mV DC (i.e. 5%). The limiting DFT seems to be about 150-200 μm. This value should be investigated in detail in laboratory settings and on a theoretical basis by means of simulation (FEM), in order to get a useful guideline for future standards and recommendations. It is noted that primary anode spacing of up to a maximum of 3 meters was used in all installlations, although most protected objects are relatively small and therefore have a total size which allows for a 1-dimensional, single primary anode lay out. Operational measurements on the voltage drop in the anode system, suggest a wider spacing may be allowed without loss of functionality. This should be further investigated.

4 Conductive coating performance and failure

A conductive coating is applied as a coating and can fail like an ordinary coating. At the same time, this coating has a technical function as a means of current distribution and as an anode in an electrochemical cell. If this function is not performed to meet the required levels of polarisation at the reinforcing steel to pore water interface, the system is deemed as 'failed'. In general the condition (evaluated as a coating) and performance (evaluated as an anode) of the conductive coating will be strongly dependent of:

- Surface preparation prior to coating application
- Environmental conditions during application
- Exposition of the anode surface during the service life
- Coating type (binder-filler-combination)
- Age of the anode material
- Local anode current density (cumulative over time and any peak values over a substantial prolonged period)

The first four points are determent of the general life time expectancy of a coating. Based on general experiences, an acrylic coating has an estimated life expectancy of 10 years and a silicate based coating of 20 years. If normal surface preparation requirements and/or environmental conditions during application are not met, then a premature failure of the anode system as a coating is to be expected. Such a failure has been observed in 1 installation: poor surface preparation has led to local debonding of the coating at such a scale and to such an extent that substantial maintenance measures needed to be taken. After maintenance the 'failed' installation was functional again.

The last four points are determent of the local aging effects associated with the anodic current. At sites where this anodic current density is too high (the threshold is depending on both anode material and concrete permeability, but pessimistically can be estimated as 20 mA/m^2_{anode}), the local anodic reaction products cause acidification. This in turn will lead to dissolvement of the cement-stone and subsequent debonding of the coating. In early stages these 'hotspots' show as colour spots in the top coat, as most acrylic top coats tend to colour slightly yellow and beige due to the high(er) acid production at the anode with the local high current density.

This process is complex as it is influenced by many factors. The temporal anode current density is mainly dependent of current demand, in turn determined by the local surface of steel to be protected per unit of the anode surface (steel density) and the factors influencing steel corrosion (i.e. chloride content, cover thickness, concrete quality etc.), local system resistance (the electrical resistance of the concrete cover in between the steel and the anode), and the temperature.

In general high demanding situations will result in reduction of the life time expectancy of the conductive coating anode. This can in turn lead to local failure of the anode as a coating. As seen in the CP systems monitored the 'failure mode', the mean service life until failure, and the extend of the failures observed (expressed as a surface percentage of the total system), varies largely.

In the 108 CP installations monitored, only 18 failed at some point in the service life. Out of these 18, a large group of 12 installations failed due to a systematic failure of the anode material itself. As this anode material (based on intrinsically conductive polymers) has an intrinsic limitation on the maximum applied voltage of 2 VDC, these systems lacked the ability to perform and meet the criteria as set out in EN12696 (i.e. 100 mV depolarisation), in some case directly after energizing and start-up (where the application was 'in-door') and in other cases over time. In general, the system resistance (resistance between anode and reinforcing steel) will increase over time. Although this might be due to the drying out of the concrete, the improvement of the specific environmental factors in the direct vicinity of the reinforcing steel, and the 'aging' of the anode, the observed data in these projects suggest that the drying out of the concrete is by far the dominant factor. As this system resistance increases, the performance of the installations with this specific type of anode material decreased and as there was no way to set the applied protective voltage to higher levels, inevitably these installations failed.

The failure of 5 other installations is accounted to leakages of water in or on the concrete, causing failure of the CP system. In these cases clear examples can be found where the general increase of resistivity (due to drying out) is locally overcompensated by the high water content due to leakages. Local paths of low resistance in combination with a general higher applied voltage (due to the general drying out of the concrete) lead to a locally high anodic current density, local acidification and hence local anodic failure (mostly due to debonding of the coating). As such, not only the local high water load should be held accountable but also the large differences within one zone in the resulting system resistances. These combined extremes lead to under- or overprotection at either of the extremes, which in turn will lead to failure.

In general, the monitored CP installations were all started (energised) at an initial setting of 2 VDC protective potential. In most installations after a few years a stable end value of 4-5 VDC was reached at which the anode had to be operated to meet the criteria of EN12696 (i.e. 100 mV depolarisation in general). It is noted that in some installations the applied voltage remained low at 2-3 VDC and in other installations values as high as 6-8 VDC were needed. These 'special' circumstances can all be accounted for as either being 'wet' or 'dry' when compared to the general circumstances.

As the applied protective voltage will result in a given protective current, it is worth noting that initial values of the protective current density are high but will soon get lower to more common values. Depending on circumstances, and not in the least on anode type, the initial current densities are commonly about 20-70 mA/m^2_{anode}. Within 24 hours after energizing these values tend to drop to values corresponding to 5-10 mA/m^2_{steel}, which in general correspond to about 5 mA/m^2_{anode}. In the long term the current density tends to values of 1-2 mA/m^2_{anode}, as more and more of the protected steel is passivated.

In all installations the 100 mV criterion from EN12696 can be met, provided the reference electrodes stay functional during the service life (but this is a subject for future evaluations), except for those situations where either extreme drying or wet conditions can be obtained. In those drying cases steel potentials are in all cases way more positive than -150 mV CSE, and are considered to be indicative of non-corroding steel. In those extremely wet conditions, instant-off potentials tend to be very low (more negative than -700 mV CSE), and are considered to be indicative of non-corroding steel due to oxygen depletion (although in some cases depolarisation is still observed, in most cases this depolarisation is way to slow to provide a sufficient, i.e. 100 mV depolarisation, within 24 hours).

5 Conductive coatings life time expectancy

As for all coating systems, the life time expectancy of conductive coatings is strongly depending on surface preparation prior to application and environmental conditions during application. If the minimum requirements (depending on the anode / binder type, these may vary) are not met, the life time expectancy will be reduced.

As in general with coatings, conductive coatings need maintenance. This means that periodical cleaning, touch up of top coats and local repairs should be accounted for. In general, these kinds of maintenance works would be scheduled for example after 7 and 15 years of age for the coating system. It can be expected that maintenance works on a minor scale are also necessary when coatings are used as an anode system. In the projects monitored, minor maintenance works were carried out, resulting in better performance (as an anode) and extended service life.

Depending on anode / binder type a life time expectancy of 10-20 years is appropriate. In the monitored projects these expectancies were met and even surpassed. In general, life times of 15-20 years (and maybe even more) may be well achievable. In the monitored installations, the used silicate based anodes showed the least number of (and the least extended size) failures and in all cases no signs of ageing. Based on the binder type a longer life time might be expected and 20 years of life time might be well achievable, but it is noted that the field applications in The Netherlands only reach up to 16 years of life time. Further monitoring of these installations will be needed to assess the life time expectancy of these systems up to failure.

As a conclusion it is stated that in 108 installations in The Netherlands, it has been shown that CP provides an effective and efficient way to maintain concrete and extended the service life of the involved concrete constructions. Failures are scarce, avoidable and solvable. A life time expectancy of 15-20 years for CP systems based on conductive coatings can readily be obtained with available technology and practices based on experience.

6 Recommendations for design an application of conductive coating anodes

Based on the experiences from the monitored installations, some general recommendations are made to obtain a long service life with conductive coating anodes for CP. These recommendations are:

- Prior to installation of the anode, prepare the concrete in order to obtain a sound and clean surface.
- Respect the environmental conditions during application, as set by the manufacturer of the anode material.
- Apply the anode material as specified by the manufacturer, but assure a minimal DFT on all locations of 200 µm.
- Use a durable primary anode. Therefore do not use as a primary anode: silver band, nickel tape or stainless steel tape.
- For primary anode spacing a safe value for maximum spacing is 3 m[1] (until further research is done, which might alter this value to higher allowed spacings).
- When using primary anodes with a copper core, be aware that the use of steel power tools and steel hammers might damage the outer clad layers of the primary anodes when these anodes are hit. Avoid the usage of these tools, or at least avoid direct contact.
- Be aware of leakages within a zone. Local load of water, especially when this water can get into the cover of the protected concrete, may lead to high anodic current densities and therefore local failure of the coating due to debonding.
- In designing a CP system, separate parts with a significant difference in moisture or water load (exposition), as much as reasonably achievable, into separate zones.
- Monitoring of CP systems, especially those based on impressed current (ICCP), is essential and should be carried out on a regular basis, in accordance with EN12696.
- During the service life maintenance of the anode system (including eventually applied top coats) is needed. This should be scheduled within a monitoring scheme or incorporated in the long term maintenance planning of the total construction.
- Whilst the CP system will provide protection of the reinforcing steel, normal maintenance of other construction parts is still needed, e.g. joints. These parts with relevance towards the service life (performance and durability) of the anode system should be addressed and be made part of either the monitoring scheme or the long term maintenance planning of the total construction.

References

[1] L. Bertolini, B. Elsener, P. Pedeferri, E. Redaelli, R.B. Polder, *Corrosion of Steel in Concrete* (2013)

[2] EN1504-9, *Products and systems for the protection and repair of concrete structures - Definitions, requirements, quality control and evaluation of conformity - Part 9: General principles for the use of products and systems principles* (2008)

[3] P.M. Chess, J.P. Broomfield, *Cathodic Protection of steel in concrete and masonry* (2014)

[4] EN-ISO 12696, *Cathodic protection of steel in concrete* (2016)

[5] R.B. Polder, W.H.A. Peelen, *Durability of Reinforced Concrete from Composition to Protection: Selected Papers of the 6th International RILEM PhD Workshop: 25 Years of Experience with Cathodic Protection of Steel in Concrete in the Netherlands* (2013)

[6] R.B. Polder, *CUR-Aanbeveling 45 Kathodische Bescherming van wapening in betonconstructies (translates to: CUR recommendation 45 Cathodic Protection of reinforcement in concrete constructions)* (1996)