Current distribution and throwing power of galvanic cathodic protection with discrete anodes in reinforced concrete beam or column elements

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Abstract. Galvanic cathodic protection (GCP) of steel in concrete by means embedded discrete anodes is a commonly used repair method to reduce or prevent steel reinforcement corrosion. The design and efficiency of the system depends greatly on the corrosion activity of the steel reinforcement and electrical resistivity of the concrete. In this research, the influence of chloride concentration and cement type in the concrete on the current distribution and throwing power of GCP with discrete anodes is investigated for linear concrete elements such as beams or columns. Results show a high throwing power (> 500 mm) of the GCP system for concrete with a CEM I cement (low resistivity) and limited chloride contamination. For concrete with a severe contamination of chlorides (2 m% by mass of cement) or high electrical resistivity (e.g. by the use of CEM III/A cement), the throwing power is greatly reduced to values of 60 mm and 110 mm, respectively. Consequently, based on the 100 mV depolarization criterium (EN ISO 12696:2016), GCP with discrete anodes was found to be most efficient for concrete with relatively low resistivity and limited corrosion activity of the steel reinforcement (related to chloride concentration in the concrete).

1 Introduction

Cathodic protection (CP) of steel in concrete is a commonly used repair technique to significantly reduce reinforcement corrosion in concrete structures [1, 2]. One principal method of cathodic protection is through the use of galvanic anodes, also commonly referred to as galvanic cathodic protection (GCP). Galvanic anodes exist in different forms and shapes, either applied on the concrete surface or embedded within the concrete. One commonly used and commercially available type of galvanic anode is the embedded discrete anode (also called point anode) consisting of a zinc core in an activation encapsulation [3 – 6].

For the design of a GCP system with embedded discrete anodes, the anode spacing is one of the most important design parameters, mainly depending on the throwing power of the anodes (i.e. the radius around the anode in which a sufficient current density is supplied to the steel reinforcement to achieve a complete corrosion protection). The throwing power of CP system with discrete galvanic anodes is influenced by a number of factors, such as density of the steel reinforcement, resistance of the concrete and corrosion activity of the steel [7, 8]. The last two parameters are also depending on the chloride contamination of the concrete and the relative humidity and temperature in the concrete (and the environment) [4].

For chloride contaminated concrete structures exposed to atmospheric conditions, very little experimental data is available in literature regarding the distribution of galvanic protection current and the throwing power of a GCP system with discrete anodes.

The main objective of the present research study is the experimental determination of the galvanic current distribution and throwing power of a GCP system with embedded discrete anodes for linear concrete elements such as beams or columns in order to determine an appropriate anode spacing in the design of a GCP system. The effect of chloride contamination in the concrete (related to corrosion activity of the steel reinforcement) and cement type (strongly influencing the resistivity of the concrete) are investigated.

2 Materials

2.1 Reinforced concrete specimens

Reinforced concrete specimens with dimensions of 1200 mm x 150 mm x 150 mm were prepared. All specimens contain 22 steel stirrups (BE500S) with dimensions of 100 mm x 100 mm (diameter 10 mm) and 4 longitudinal glass fiber reinforced polymer (GFRP) rebars (diameter 10 mm). The rebar configuration of the specimens is shown in Figure 1.

The stirrups are placed with an intermediate distance of 50 mm, except in de middle of the specimens where a distance of 100 mm between stirrups was adopted for the installation of a discrete galvanic anode (see Figure 1).
Due to the use of GFRP rebars, all stirrups are electrically separated from each other.

The stirrups in both halves of the specimens at equal distance from the centre are electrically connected to each other by means of an insulated copper wire. For each connected couple of stirrups at equal distance from the centre, an electrical connection to the exterior was made by means of a black insulated copper wire (see photo in Figure 1).

In one half of each specimen, decay probes made of TiMMO strips were placed in the centre of each stirrup as reference electrode (see Figure 1). The decay probes have a connection to the exterior with a blue insulated copper wire and are used for depolarization measurements.

Four different concrete mixtures were made, given in Table 1. Each mix contains the same aggregate proportions, a cement content of 320 kg/m³ and a water to cement ratio of 0.5. The exact mix composition can be found in [7]. The mixes differ either by the type of cement or the chloride concentration in the mix. For mixes 2, 3 and 4, chlorides were added to the mixture by dissolving NaCl in the mixing water. To each mix, 2.0 ml of superplasticizer per kg of cement was added. One concrete specimen was made for each concrete mix.

Table 1. Concrete mixtures.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Cement type</th>
<th>Chloride concentration (m% by cement mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CEM I 52.5 N</td>
<td>0 m%</td>
</tr>
<tr>
<td>2</td>
<td>CEM I 52.5 N</td>
<td>1 m%</td>
</tr>
<tr>
<td>3</td>
<td>CEM I 52.5 N</td>
<td>2 m%</td>
</tr>
<tr>
<td>4</td>
<td>CEM III/A 42.5 N</td>
<td>1 m%</td>
</tr>
</tbody>
</table>

After casting, the concrete specimens were stored in an air-conditioned room at a temperature of 20°C and a relative humidity of at least 95% for 24 hours. Subsequently, the specimens were demolded and stored in the aforementioned room until an age of 28 days.

After the 28-day curing period, the concrete specimens were placed in an outside unsheltered environment, exposed to natural climate conditions in Belgium, for a period of about 10 weeks. Thereafter, the discrete galvanic anodes were installed in the specimens (see 2.2).

### 2.2 Discrete galvanic anodes

The discrete galvanic anodes used in this research are commercially available anodes type ‘GalvaShield CC4’ produced by Vector Corrosion Technologies Ltd. The anodes consist of a sacrificial zinc core with a mass of 120 ± 5 grams, surrounded by an activated cementitious mortar with a pH of 14 or higher. The anode units have a diameter of 36 mm and a length of 100 mm.

One anode unit was installed in the centre of each concrete specimen (see Figure 1). Therefore, a core with a diameter of 45 mm was drilled in the centre of the concrete specimens and the anode units were placed in the borehole surrounded by an embedding mortar according to the instructions of the manufacturer. The steel tie wire of the anodes was connected with a red insulated copper wire to the exterior.

After the installation of the anode units, the concrete specimens were placed in an outside unsheltered environment, exposed to natural climate conditions in Belgium.

### 2.3 Concrete specimens for resistivity measurements

Concrete resistivity is an important influencing parameter on the efficiency and throwing power of galvanic cathodic protection systems [8].

In order to measure the resistivity of the concrete mixtures, separate specimens with dimensions of 100 mm x 100 mm x 50 mm were made containing two embedded stainless steel bars (diameter 6 mm), positioned 50 mm apart. For each concrete mixture, three replicate samples were made.
3 Methods

3.1 Initial potential and current measurements

Initial measurements of the steel potential of each couple of stirrups at a distance of 50 mm up to 550 mm from the discrete anode with respect to the installed TiMMO decay probes were performed before connecting the galvanic anode to the stirrups (= ‘OFF’ potentials) by means of a high impedance voltmeter.

Subsequently, the installed galvanic anode was connected to all steel stirrups of the specimen by means of the copper wire connections (see Figure 2). Immediately after the connection, the potential of each couple of stirrups with respect to the installed TiMMO decay probes was measured again (= ‘ON’ potentials) and the galvanic current output to each couple of stirrups was measured by means of a multimeter with a resolution of 0.1 µA.

![Figure 2. Connection and measurement setup.](image)

3.2 Depolarisation measurements

On a monthly basis, the galvanic current output to each couple of stirrups for all concrete specimens was measured after which a depolarisation measurement was performed.

The depolarisation was performed by interrupting the connection between the installed galvanic anode and the steel stirrups. The total period of depolarization was 24 hours, after which the connection between the stirrups and the galvanic anode was re-established. During the depolarisation, the steel potential of each couple of stirrups was measured at the following times:

- Before the start of depolarisation (with anode and stirrups connected) = ‘ON’ potential.
- Instantly after disconnection of the anode = ‘Instant-OFF’ potential.
- 0.5h, 1h, 2h, 4h and 24h after the start of the depolarisation (≈ 0.5h, 1h, 2h, 4h and 24h ‘OFF’ potentials).
- At the end of the depolarisation, when the anode is reconnected with the steel stirrups.

The depolarization of each couple of steel stirrups was calculated as the difference between the measured ‘OFF’ potential at a certain time after disconnection and the ‘Instant-OFF’ potential.

Based on the measurements, the depolarization of the steel reinforcement in function of the distance to the galvanic anode is determined, thus allowing to calculated the throwing power of the system. The throwing power is defined as the distance from the anode where 100 mV depolarization is achieved within 24 hours [7, 8], according to the 100 mV depolarization criterium described in the European standard EN ISO 12696:2016 [10].

3.3 Resistivity measurements

The resistivity of each concrete mixture was measured on the separate concrete specimens with two embedded electrodes (stainless steel bars), according to the method described in the Dutch recommendation document regarding cathodic protection of steel in concrete structures, CUR-Aanbeveling 45 [11, 12].

The resistance between the two embedded stainless steel bars in the specimens is measured by means of an LCR meter (measurement frequency of 120 Hz). Subsequently, the resistivity of the concrete is calculated by multiplying the measured resistance by a cell constant which is experimentally determined for the specific geometry of the specimen [12].

4 Results and discussion

4.1 Start-up of the galvanic cathodic protection

The measured corrosion potential of each couple of stirrups in the concrete specimens (at different distance from the location of the anode) before connection of the galvanic anode is shown in Figure 3.

![Figure 3. Steel corrosion potential prior to the connection of the galvanic anode.](image)

The corrosion potential of the different stirrups in one concrete specimen is nearly equal before the start of galvanic CP for each concrete mix. However, the corrosion potential is clearly depending on the amount of chlorides in the concrete mix in the sense that the potential values are more negative when the chloride content in the concrete is higher. This is a logical result, since a higher chloride content leads to a higher risk for
reinforcement corrosion, which in turn leads to a more negative corrosion potential of the steel [13].

The mean corrosion potential of the concrete specimens with 1 % Cl by cement mass (both the mixtures with CEM I and CEM III/A) is 60 mV more negative compared to the concrete specimen without mixed-in chlorides, while for the specimens with 2 m% Cl, the mean corrosion potential is 150 mV more negative compared to the concrete specimen without mixed-in chlorides.

When the galvanic anode is connected to the steel stirrups, the measured potential shifts towards more negative values due to the negative potential of the zinc anode. The negative shift in potential is higher for a shorter distance from the anode (see Figure 4).

![Figure 4](image)

**Figure 4.** Steel corrosion potential directly after connection of the galvanic anode.

Table 2 shows the negative potential shift of the stirrups closest to the anode (50 mm) and farthest from the anode (550 mm).

<table>
<thead>
<tr>
<th>Mix</th>
<th>Shift in potential after anode connection</th>
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<tbody>
<tr>
<td></td>
<td>50 mm from anode</td>
</tr>
<tr>
<td>1</td>
<td>323 mV</td>
</tr>
<tr>
<td>2</td>
<td>208 mV</td>
</tr>
<tr>
<td>3</td>
<td>161 mV</td>
</tr>
<tr>
<td>4</td>
<td>267 mV</td>
</tr>
</tbody>
</table>

For mixes 1 and 2 (CEM I with 0 % and 1% Cl by cement mass) there is a relatively large negative shift in potential, both close to the anode, but also at a larger distance from the anode. For mix 3 (CEM I with 2 % Cl by cement mass), the shift in potential is much lower, especially farther away from the anode. The negative potential shift in mix 4 (CEM III/A with 1 % Cl by cement mass) is relatively high very close to the anode, but drops to low values very fast (only 10 mV shift at a distance of 250 mm from the anode).

The galvanic current output from the anode to the steel stirrups shortly after the connection is given in Figure 5.

![Figure 5](image)

**Figure 5.** Galvanic current output from anode at start.

The galvanic current is fairly similar for the different concrete mixes, indicating that the level of chloride contamination in the concrete mix has little influence on the galvanic protection current supplied by the anode. This is in agreement with previous research performed with similar embedded galvanic anodes [7].

As expected, the current output is highest closest to the anode (ranging from 8 to 13 mA / m² steel). For all mixes, the current drops exponentially with distance from the anode to values lower than 2 mA / m² steel from a distance of 200 mm away from the anode.

For the concrete specimen of mix 3 (CEM I with 2 % Cl by cement mass), the current shows a large fluctuation at a distance larger than 200 mm away from the anode and at some locations a negative current is measured. This may be related to the formation of macro-cell corrosion elements between adjacent stirrups, rather than current from the anode to the stirrups.

### 4.2 Evolution of galvanic current output

Figure 6 shows the measured galvanic current in function of the distance from the anode at 5 different measurement times for mix 1 (CEM I with 0 % Cl by cement mass). In Figure 7, the evolution of the total current from the anode to all steel reinforcement in the specimens for all concrete mixes is plotted.

The current output is highest at the start, decreases during the first 17 weeks, subsequently remains relatively stable until 30 weeks (see Figure 7) after which an increase in current occurs. The decrease and subsequent increase in current can be related to seasonal changes in temperature and relative humidity of the environment. Especially the temperature dependency of the galvanic current has been noticed in previous studies for similar galvanic anodes [3, 7].
4.3 Depolarisation and throwing power

In total, 10 depolarisation measurements (24-hour) were performed on a monthly basis.

An example of the results of the measured depolarisation as a function of the distance from the anode at different times since the start of depolarisation (0.5h, 1h, 2h, 4h and 24h) is given in Figure 8 to Figure 11 for each concrete mixture during one of the monthly depolarisation measurements.

For concrete mixes 1 and 2 an increasing level of depolarisation in time is noticed during the 24-hour depolarising period (see Figure 8 and Figure 9). For mix 1, the depolarisation level increases by 60 to 75 mV from 0.5h to 24h. For mix 2, the increase is 45 to 55 mV. Concrete mixes 3 and 4 on the other hand do not show much difference in level of depolarisation between 0.5h and 24h, mostly lower than 10 mV.

It was noticed that the depolarisation did not show a large variation in time during the 10 months measuring period, especially at larger distances from the anode. Figure 12 gives an overview of the mean depolarisation in function of the distance from the anode for all concrete mixes.
The mean depolarisation based on all measurements in a 10 month period (Figure 12) shows that the concrete mixtures without mixed-in chlorides and with a relatively limited chloride content of 1 m% by mass of cement show a relatively high level of depolarisation. For mix 1 (CEM I with 0 % Cl by cement mass), the depolarisation is higher than 100 mV at all measured distances from the anode up to 550 mm. For a higher chloride concentration of 2 m% by mass of cement, a much lower level of depolarisation of the steel is obtained, only reaching 100 mV close to the anode (at 50 mm distance).

For mix 4 with the CEM III/A cement, the depolarisation close to the anode is higher than for the other mixes, but decreases rapidly going farther away from the anode. At a distance larger than 100 mm from the anode, the level of depolarisation is already lower than 100 mV.

Based on the obtained average 24-hour depolarisation measurement results (Figure 12), a throwing power of the embedded galvanic anodes was calculated as the distance from the anode where 100 mV depolarisation is achieved. The results of the determined throwing power are given in Table 3.

**Table 3.** Throwing power of the embedded galvanic anode, based on the 100 mV depolarisation criterion [10].

<table>
<thead>
<tr>
<th>Mix</th>
<th>Designation</th>
<th>Throwing power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CEM I - 0 m% Cl</td>
<td>&gt; 550 mm</td>
</tr>
<tr>
<td>2</td>
<td>CEM I - 1 m% Cl</td>
<td>520 mm</td>
</tr>
<tr>
<td>3</td>
<td>CEM I - 2 m% Cl</td>
<td>60 mm</td>
</tr>
<tr>
<td>4</td>
<td>CEM III/A - 1 m% Cl</td>
<td>110 mm</td>
</tr>
</tbody>
</table>

The obtained average throwing power generally decreases with an increasing chloride concentration in the concrete, which is in agreement with literature [7, 14, 15], as it has been established that the throwing power of CP systems is higher for passive steel reinforcement compared to actively corroding steel due to the higher polarizability of passive surfaces.

The results show a very large decrease in throwing power when the chloride concentration in the concrete is increased from 1 m% to 2 m% by mass of cement (throwing power more than 8 times lower for the latter). Possibly this could be related to an increased corrosion activity of the reinforcement in the specimen with 2 m% Cl by cement mass, due to a surpassing of the critical chloride concentration for initiation of corrosion. However, in most studies, a chloride concentration of 1 m% by mass of cement is already considered critical [16].

When the chloride concentration in the concrete is kept constant at 1 m% by mass of cement, but the cement type is changed from CEM I to CEM III/A, a large decrease (factor of about 4.7) in throwing power is noticed. This decrease of throwing power can mainly be attributed to the higher resistivity of the concrete (see 4.4).

### 4.4 Concrete resistivity

The resistivity of the concrete mixes was measured every month at the same time when the depolarisation measurements were performed. An example of the measured resistivity of the four concrete mixes is shown in Figure 13.

![Figure 13. Concrete resistivity.](https://example.com/fig13.png)

As Figure 13 clearly shows, the resistivity of the concrete mix with the CEM III/A cement was found to be 5 to 7 times higher compared to the concrete mixes with the CEM I cement. For mixes 1, 2 and 3 with the CEM I cement, similar values for the concrete resistivity were obtained, indicating that the chloride concentration in the concrete has a very limited influence on the resistivity. This is generally in agreement with literature [17, 18] where it is stated that the effect of chloride ions in the concrete on the resistivity is relatively small, especially for concrete with a high moisture content.

### 5 Conclusions

The galvanic current density supplied by an embedded discrete anode was found to be fairly similar for all concrete mixes with a CEM I cement, indicating that chloride concentration in the concrete has limited influence on the current output of the anodes. For the concrete mix with the CEM III/A cement, the current...
density is generally lower, which can be related to the higher resistivity of the concrete.

The current density is mostly related to environmental conditions, especially the ambient temperature of the environment. At a distance of 50 mm from the embedded discrete anode, current densities up to 16 mA/m² steel were measured on summer days with a relatively high temperature (> 20°C), while in the winter period (November to February) the maximum measured current density was 5.5 mA/m² steel.

From a distance of 200 mm from the anode, the current density from the anode to the steel reinforcement was lower than 1.5 mA/m² steel for all concrete mixes at every measurement date. For actively corroding steel, a current density lower than 2.0 mA/m² steel is generally insufficient to provide complete protection against corrosion [10].

By performing monthly 24-hour depolarisation measurements, the throwing power of the GCP system with discrete anodes was determined, according to the 100 mV depolarisation criterion described in the European standard EN ISO 12696:2016 [10]. Results showed that for concrete with a CEM I cement without contamination of chlorides or with a relatively limited mixed-in chloride content of 1 m% by mass of cement, a high throwing power of more than 500 mm was obtained. However, the throwing power was drastically reduced to an average of only 60 mm when the chloride content was increased to 2 m% by mass of cement, which may be a result of an increased corrosion activity of the reinforcement due to a surpassing of the critical chloride concentration for initiation of corrosion.

When using a CEM III/A cement instead of CEM I, the resistivity of the concrete increased by a factor of 5 to 7, which lead to a large decrease in throwing power of the GCP system. The average throwing power of the concrete mix with a CEM III/A cement was 110 mm, approximately 5 times lower compared to the concrete with a CEM I cement with the same chloride concentration.

Generally it can be concluded that for concrete with a relatively high resistivity (for example due to use of cement with a large fraction of blast-furnace slag) and/or concrete with a severe contamination of chlorides, causing a significant drop in corrosion potential of the steel reinforcement, throwing power of embedded galvanic anodes is very limited. Therefore, a GCP system with discrete anodes is most efficient and feasible, both practically and economically, when installed at a moment close to the initiation of corrosion, i.e. the moment where the chloride concentration in the concrete at the level of the reinforcement reaches the critical level for depassivation, and for concrete with a relatively low electrical resistivity.

Further research is necessary to determine the exact chloride concentration and/or electrical resistivity of a certain concrete composition at which the throwing power of a GCP system with discrete anodes falls below an acceptable limit (practically and economically).

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References


