

Influence of various parameters on the current distribution and protection degree of impressed current cathodic protection for reinforced concrete with TiMMO mesh anodes

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Abstract. Impressed current cathodic protection (ICCP) is an effective technique to control reinforcement corrosion in concrete structures. The efficiency and design of an ICCP system with titanium mixed metal oxide (TiMMO) anodes in a mortar overlay is strongly influenced by the current distribution to the different reinforcement layers of a reinforced concrete element. An in-depth experimental study is performed to investigate the effect of various parameters on the current distribution and degree of corrosion protection: (i) chloride content, (ii) cement type, and (iii) reinforcement configuration. 24-hour depolarization measurements (EN ISO 12696:2022) indicate that an increase in chloride concentration in the concrete, related to an increase in the rate of reinforcement corrosion, leads to a general decrease in the degree of protection. The use of a CEM III/A cement leads to a large increase in concrete electrical resistivity compared to concrete with an ordinary Portland cement (CEM I). This causes a lower total current output to the reinforcement and a less uniform distribution of current. Finally, a lower steel reinforcement density resulted in a larger current density, as the total current is distributed over a smaller steel surface area, causing higher depolarization values.

1 Introduction

Reinforcement steel corrosion is one of the main degradation mechanisms of reinforced concrete (RC) structures. Corrosion can be induced by carbonation or chloride contamination and can drastically reduce the durability/service life of RC structures [1, 2]. Over the years, several techniques have been developed in order to tackle reinforcement corrosion, such as cathodic protection (CP).

One method to achieve CP of the reinforcement steel is by impressing a current using a direct current (DC) source, generally referred to as impressed current cathodic protection (ICCP). The applied external protection current will polarize the steel in the cathodic direction and hereby reduce the anodic (corrosion) reaction rate [3].

The design of an ICCP system is strongly influenced by the current distribution to the different reinforcement layers of a RC structure. It is difficult to make an optimal ICCP system design due to the non-uniform character of the current distribution. The main goal is to both protect adequately different reinforcement layers against corrosion and to avoid overprotection. It is difficult to predict the current distribution behavior due to the numerous influencing parameters [4]. There is a lack of existing knowledge on the current distribution and protection degree of ICCP systems. Therefore, several

parameters (the anode type/configuration, concrete resistivity, corrosion activity, applied current density and reinforcement density) are studied and discussed in this paper.

The objective of this study is to experimentally determine the current distribution and protection degree of an ICCP system installed on atmosphere-exposed RC elements with three layers of reinforcement. A titanium mixed metal oxide (TiMMO) mesh anode is applied on top of the elements so that the distance from the anode to the reinforcement layers gradually increases. The influence of the cement type, chloride content (mixed in chlorides) and reinforcement density on the current distribution and protection degree are examined.

2 Test set-up

Seven RC prisms are produced with the following dimensions: 200 mm x 200 mm x 300 mm. Each prism is provided with three reinforcement meshes distributed over the depth of the prism, where each mesh consists of 4 steel rebars (BE500S) with a length of 150 mm. The mesh configuration is visualised in Figure 1. Per prism, the diameter of the rebars is kept constant with a standard diameter of 16 mm (corresponding to a reinforcement density of 1 m² steel / m² concrete). To investigate the influence of the reinforcement density, one specimen is provided with rebars with a diameter of

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8 mm (i.e. 0.5 m² steel / m² concrete) and one specimen with rebars with a diameter of 25 mm (i.e. 1.5 m² steel / m² of concrete) (prism 6 and prism 7 respectively, Table 1).

The reinforcement configuration is shown in Figure 1. A TiMMO mesh anode is installed on top of the prisms, where a concrete cover of 30 mm is provided between the anode and the first reinforcement layer. The centre-to-centre distance between the reinforcement layers is set at 100 mm. Glass fibre reinforced polymer (GFRP) rebars (diameter 6 mm) are used to keep the reinforcement meshes in place during casting.

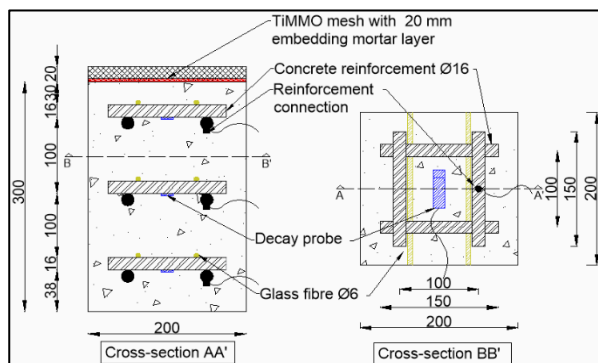


Fig. 1. Schematic cross-sections of the RC prisms (dimensions in mm).

Each mesh is connected with a black insulated copper wire (section 2.5 mm²). Per prism, the three insulated copper wires can be connected externally (outside the concrete) to provide one connection to the DC source. The current flowing to each reinforcement layer can thus be measured separately. Decay probes (TiMMO reference electrodes (RE's)) of 1 cm x 5 cm are installed in the centre of each mesh in order to perform depolarization measurements (see Figure 1). Each decay probe is connected to a blue insulated copper wire (section 2.5 mm²).

Table 1. Characteristics of the reinforced concrete prisms.

Prism number	Cement type	Cl concentration [m% by cement mass]	Rebar Ø [mm]
1	CEM I 52.5 N	1	16
2	CEM I 52.5 N	0	16
3	CEM I 52.5 N	2	16
4	CEM I 52.5 N	2 with ACT(*)	16
5	CEM III/A 42.5 N LA	1	16
6	CEM I 52.5 N	1	8
7	CEM I 52.5 N	1	25

(*) ACT = accelerated corrosion test

Four different types of concrete blends are produced with a different chloride content or cement type (see Table 1). The chlorides are added to the concrete by mixing NaCl with the mixing water until the NaCl is fully dissolved. The cement content (320 kg/m³), water/cement factor (0.5) and aggregate properties are kept constant for the different concrete mixtures. 2 ml of superplasticizer per kg cement is added to every

mixture. The detailed concrete mix compositions can be found in [5].

Prism 4 is subjected to an accelerated corrosion test (ACT) before the installation of the TiMMO mesh anode, to obtain an increased level of corrosion. More information about the test set-up can be found in [6, 7].

After pouring the concrete, the specimens are stored in a condition controlled environment with a temperature of 20°C and a relative humidity (RH) of at least 95% for a curing period of 28 days. The formwork is removed 24 hours after the casting.

After the curing period, the concrete prisms are kept in an unsheltered outside environment, where they are exposed to the weather conditions of Ghent (Belgium) for the entire study period during the winter/spring with different temperatures [-2°C;22°C] and RH [20%;96%].

A TiMMO mesh is used as anode in this study: (i) diamond shaped wires with dimensions of 85 mm x 38 mm with a nominal current density of 20 mA per m² for 100 years lifespan, (ii) a mesh of 175 mm x 175 mm installed on top of each prism and imbedded in a cementitious mortar overlay (thickness of 20 mm). Additionally, a titanium current distribution strip of 12.7 mm x 120 mm is spot welded to each TiMMO mesh. A red insulated copper wire (section 2.5 mm²) is connected to provide a DC source connection (i.e. the anode contact). The TiMMO mesh anode systems are installed 90 days after the production of the concrete specimens.

For the overlay mortar and each concrete mix, additional specimens are cast (100 mm x 100 mm x 50 mm), identically cured and stored as the concrete prisms and the resistivity of the samples is determined by means of the two-electrode method as described in [8] using an LCR meter at 120 Hz. Therefore, two stainless steel rebars (diameter 6 mm and length 150 mm) are embedded in the concrete/mortar specimens with a spacing of 50 mm.

3 Methods

3.1 Current and ICCP start-up potential measurements

Before the start-up of the ICCP system, the potential of each reinforcement mesh is measured relative to their corresponding decay probe, referred to as the start-up OFF potentials or corrosion potentials. A high impedance voltmeter is used to execute these potential measurements.

Thereafter, the voltage-controlled power supply is switched on with a start value of 2 V. The TiMMO mesh anode is connected to the positive terminal of the source and the reinforcement meshes are connected to the negative terminal. Immediately after the start-up, the reinforcement potentials are measured again relative to their corresponding decay probes, referred to as the start-up ON potentials.

The current flowing to each reinforcement layer is measured at regular time intervals (three to four times per week) by placing a multimeter (resolution: 0.1 µA) in the circuit.

3.2 Depolarization measurements

Periodically (every two weeks), depolarization measurements are performed to determine the degree of protection of the reinforcement, generated by the protection current. Based on the results of the measurements, the source voltage is adjusted.

A depolarisation measurement is performed by disconnecting the reinforcement from the negative DC source terminal for a period of 24 hours. Hereby, the steel potential, compared to the corresponding decay probe, is measured at subsequent times: (i) before the execution of depolarisation measurement, referred to as the ON potential, (ii) immediately after the disconnection of the reinforcement, referred to as the Instant OFF (I/O) potential, (iii) 0.5h, 1h, 2h, 3h, 4h, 8h and 24h after the reinforcement disconnection, referred to as the 0.5h, 1h, 2h, 3h, 4h, 8h and 24h OFF potential and (iv) after reconnecting the reinforcing steel to the negative terminal.

The difference between the I/O potential and the OFF potential is determined at a certain moment during the depolarization measurement. As such, the depolarization value is assessed for each reinforcement layer: the 24h depolarization value is determined and the 100 mV criterium is checked according to the EN ISO 12696:2022 standard [9]. This criterium can be used to determine the distance from the anode system where the protection current density is sufficient (throwing power) to protect the steel.

4 Results and discussion

4.1 ICCP start-up

The steel potential of the different reinforcement layers, in function of the distance to the anode system, relative to their TiMMO RE's before the start-up of the ICCP systems is given in Figure 2.

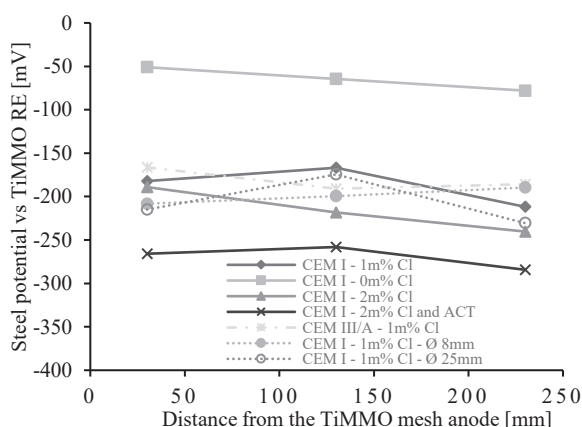


Fig. 2. Reinforcing steel potential relative to the TiMMO RE's before the ICCP start-up.

The mass percentage of chlorides mixed into the concrete mix has an influence on the steel corrosion potential. For a higher concrete chloride content, the

reinforcement steel corrosion potential will be more negative. This is consistent with findings in [5, 10, 11].

All steel potentials drop to more negative values when the DC source is turned on. The negative potential shift will reduce the anodic corrosion rate [12]. The difference in potential is presented in Figure 3. The start-up ON potentials are subtracted from the start-up OFF potentials, hence the positive values.

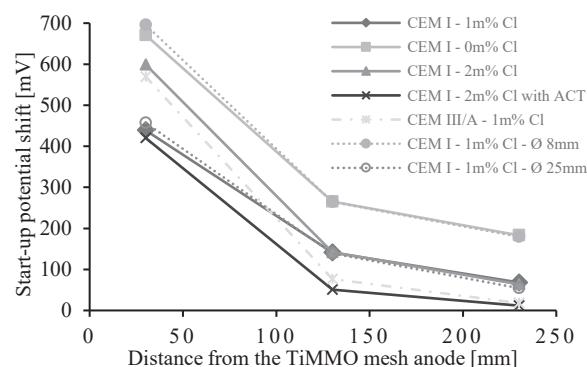


Fig. 3. The potential difference between the reinforcement start-up OFF potential and start-up ON potential.

The largest negative shift in potential can be observed for prism 2 (0 m% Cl) and prism 6 ($\varnothing$ 8mm) for the three reinforcement layers. The negative potential shift is quite comparable for the reinforcement layers at distance of 130 mm and 230 mm from the anode for prisms 1 (CEM I 1 m% Cl), 3 (2 m% Cl) and 7 ($\varnothing$ 25mm). For prism 4 (2 m% Cl with ACT) and prism 5 (CEM III/A), the negative potential shift is relatively high for the reinforcement layer closest to the anode, but decreases significantly as the distance from the anode increases. The potential shift is only 15 mV at a distance of 230 mm.

The current density per reinforcement layer is measured after the start-up of the ICCP system and is presented in Figure 4.

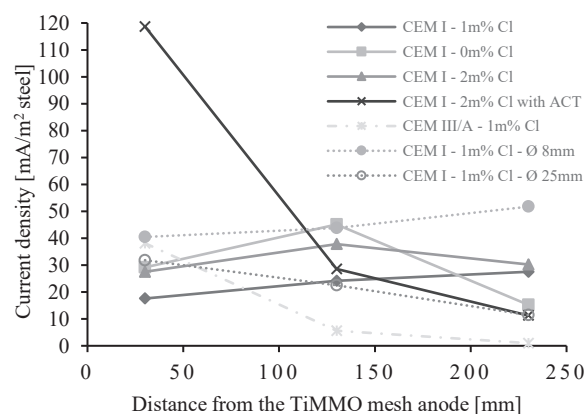


Fig. 4. Current density per reinforcement layer after start-up.

The start-up current density output does not correspond to start-up polarization trend for certain prisms. The reinforcement layer at a distance of 130 mm or 230 mm from the anode receives a higher current density than the layer the closest to the anode for prism 1 (CEM I 1 m% Cl), prism 2 (0 m% Cl), prism 3 (2 m% Cl) and prism 6 ($\varnothing$ 8 mm). The same effect was

observed by Bhuiyan et al. [13]. It was hypothesized that the anomaly in the current values could be explained by an initial macro-cell current between the reinforcement layers flowing through the ICCP system [13]. The large difference in the steel potential between the reinforcement layers after start-up could explain the formation of a macro-cell current. Due to the logical start-up polarization shift, it is assumed that the actual protection current is in line with the polarization shift trend.

For prism 4 (2 m% Cl with ACT) and prism 5 (CEM III/A), the current density distribution is in line with the polarization shift trend. This could be related to the reinforcement corrosion activity and concrete resistivity. A remark can be made on the high value of the reinforcement at an anode distance of 30 mm for prism 4 (2 m% Cl with ACT). The attraction of chloride ions of the reinforcement steel during the ACT may have caused a reduction in concrete resistivity.

4.2 Current density evolution

The current density received by the different reinforcement layers of prism 1 (CEM I 1 m% Cl) is presented in Figure 5 for six selected measurements. The source voltage is adjusted on three dates. The start-up voltage is 2 V and is increased to 3 V approximately 1.7 weeks after the start-up. Eight weeks after the start-up, the source voltage is increased to 4 V.

It is noticeable that the layer at a distance of 230 mm receives a higher current density than the reinforcement layer at 130 mm for certain moments in time and different source voltages. Again, this is assumed to be caused by a macro-cell current flowing through the system.

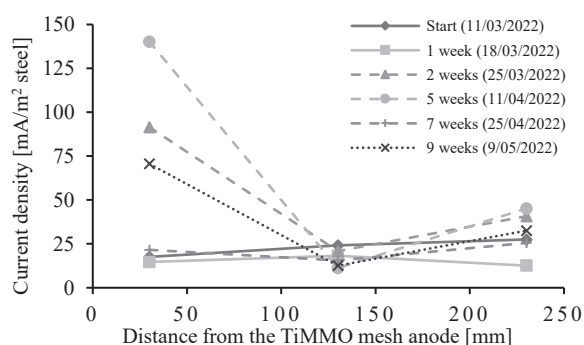


Fig. 5. Current density received by the different reinforcement layers of prism 1 (CEM I – 1 m% Cl) for six moments in time.

The total current density evolution is plotted in Figure 6 and Figure 7 for the different specimens. It is immediately noticeable that an increase in source voltage is accompanied by a general increase in total current density. The fluctuations in the total current density, for a constant source voltage, can be related to changes in the weather conditions in terms of temperature and relative humidity.

A second remark can be made on the values of the total current densities. According to the EN ISO 12696: 2022 standard, the typical current demands for steel in chloride contaminated concrete are in a range of

2 mA/m²_{st} to 20 mA/m²_{st} [9]. For the specimens with CEM I, it is clear that the average total current density is greater than 20 mA/m²_{st}. This could be explained by a scale effect. The average anode current density over the study period is 103 mA/m² concrete/anode surface for prism 1, which is significantly higher than the nominal 20 mA/m² concrete/anode surface. The size of the current distribution strip is relatively large compared to the size of the TiMMO mesh.

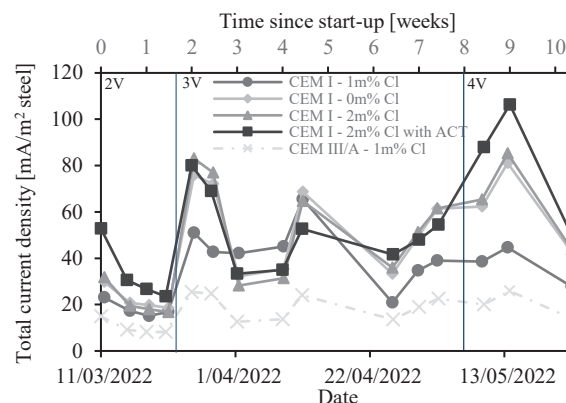


Fig. 6. Total current density evolution of prism 1 to prism 5.

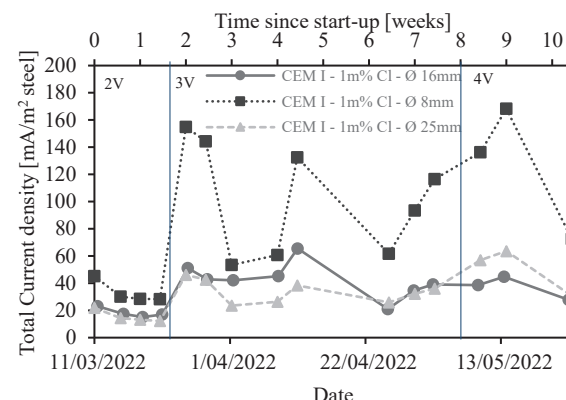


Fig. 7. Total current density evolution of the prisms with a different reinforcement density.

4.3 Depolarization measurements

Four 24h depolarisation measurements have been performed over the study period of eleven weeks. These measurements have been performed at the following moments (from start-up): after 1.6 weeks, 3.4 weeks, 7.6 weeks and 9.6 weeks.

The steel potential values, measured during the depolarization measurement 1.6 weeks after start-up, are given in Figure 8 for the three reinforcement layers of prism 1. It is clear in this example that the steel potential increases after the reinforcement disconnection, where the 24 hour potential increase is greatest for the layer closest to the anode with a value of 521 mV.

The four 24h depolarization measurement results for the three reinforcement layers of prism 1 are presented in Figure 9. The influence of the source voltage is visible for layers at a distance of 130 mm and 230 mm from the anode. A source voltage increase is accompanied by an increase in the 24h depolarisation value. For the layer

closest to the anode, this influence is less clear. An influence of environmental factors (concrete temperature and relative humidity) could explain this behaviour.

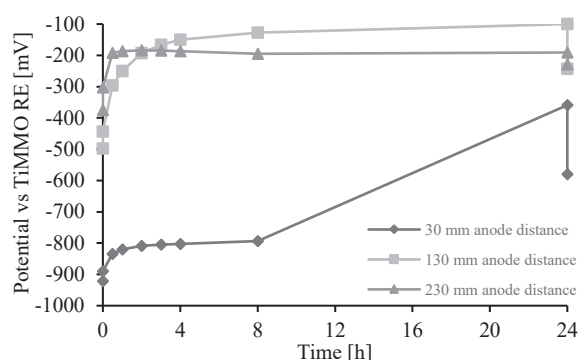


Fig. 8. Steel potential values during the depolarization measurement for prism 1 1.6 weeks after start-up.

The mean 24h depolarization values of the different specimens, based on the four executed depolarization measurements, are presented in Figure 10.

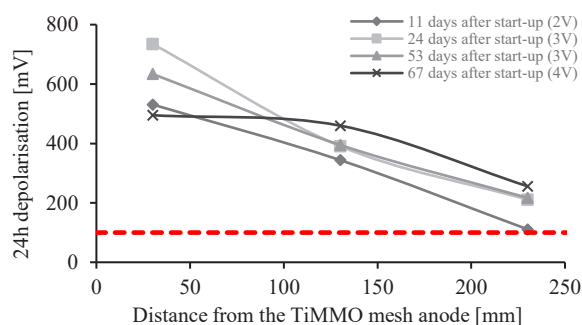


Fig. 9. The four 24h depolarization measurement results for the reinforcement layers of prism 1.

An increase in chloride content, linked to an increase in corrosion activity, is accompanied by a decrease in the 24h depolarization values and a decrease in throwing power. This is confirmed by [5, 11, 14]. The 100 mV depolarization criteria is not met for the layers at a distance of 130 mm and 230 mm from the anode for prism 4 (2 m% Cl with ACT). A remark can be made on the high mean 24h depolarization values for the layer at 30 mm from the anode for prism 1 (CEM I 1 m% Cl) and prism 2 (0 m% Cl).

The use of CEM III/A compared to CEM I cement has a noticeable impact on the degree of protection and throwing power. For prism 5 (CEM III/A), the throwing is reached at a distance of 130 mm from the anode, while the throwing power for prism 1 is beyond the limiting 230 mm. If the trendline of the prism 1 graph were to be extended, the intersection with the 100 mV line would fall at a distance of 279 mm from the anode. The ratio of these throwing power values will result in a factor of about 2. This behaviour can be attributed to the difference in concrete resistivity due to the use of a different cement type (see part 4.4).

The reinforcement density has a significant effect on the mean 24h depolarization values. The ratio between the mean 24h depolarization values for the average of the three reinforcement layers varies:

- Prism 6 (Ø8 mm)/prism 1 (Ø16 mm): 1.52
- Prism 7 (Ø25 mm)/prism 1 (Ø16 mm): 0.49

So, the degree of protection decreases with an increase in reinforcement density. For prism 7 (Ø25 mm), the throwing power has a value of around 225 mm. For prism 6 (Ø8 mm), the trendline can also be extended and will result in a throwing power value of 382 mm. This will result in the following ratios:

- Prism 6 (Ø8 mm)/prism 1 (Ø16 mm): 1.37
- Prism 7 (Ø25 mm)/prism 1 (Ø16 mm): 0.81

The throwing power decreases with an increase in reinforcement density.

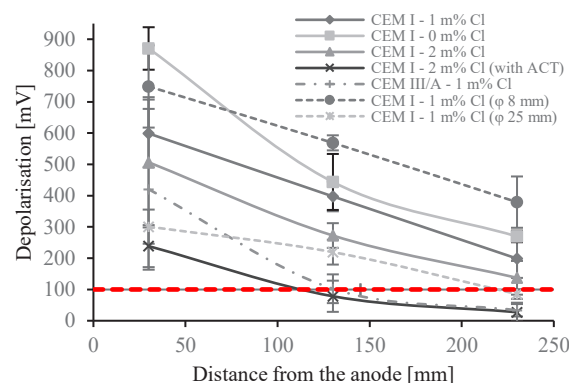


Fig. 10. Mean 24h depolarization values based on the four performed measurements.

4.4 Concrete and mortar resistivity

The concrete and mortar resistivity is measured weekly during the study period by means of the additional cast specimens. An example of a resistivity measurement is presented in Figure 11 for the four concrete mixtures and the mortar overlay mixture.

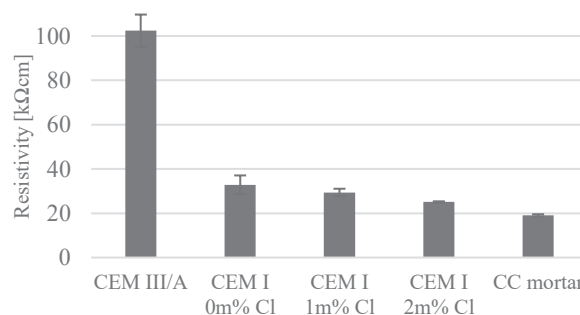


Fig. 11. Resistivity values 45 days after start-up.

It can be concluded that the use of blast furnace slag has a large impact on the concrete resistivity (Figure 11). The concrete resistivity is approximately 3 to 4 times higher for the concrete with CEM III/A compared to the concrete with CEM I cement, both with 1m% Cl by the weight of cement. The influence of the concrete chloride content is relatively small, where a small decrease in the resistivity value can be noticed with an increase in chloride content, as in agreement with literature findings [11].

The overlay mortar (CC mortar) has a lower resistivity than the CEM I concrete with 2 m% Cl by the weight of cement. It is important to report that there is

an age difference of 90 days between the production of the concrete and the mortar. As the curing age increases, the porosity decreases which leads to an general increase in concrete resistivity [15]. The resistivity values of the concrete and mortar cannot be compared due to the age difference.

5 Conclusions

In this study, it was found that the effect of chloride content on the total current density is negligible for Portland cement mixes. However, using blast furnace slag (e.g. CEM III/A) has a more pronounced effect: a clear decrease was found which might be contributed to an increase in concrete resistivity. The effect of the reinforcement density is evident, where a reduction of the reinforcement density is accompanied by an increase in total current density. A general increase in total current density can be noticed with an increase in the source voltage. The total current density depends on the environmental conditions. A peak total current density was recorded at a relatively high concrete temperature and high relative humidity.

For some specimens, a larger current is measured for reinforcement layers further away from the anode system than the closest layer, the degree of polarization is always highest for the closest reinforcement layer. It is assumed that a macro-cell current flows through the ICCP system. Due to the logical polarization trend, it is assumed that the macro-cell current has no influence on the applied protection current. This makes it difficult to determine the protection current distribution to the different reinforcement layers.

An increase in the concrete chloride content, related to an increase in the corrosion activity, is accompanied by a decrease in the average 24h depolarization values and a decrease in the average throwing. By performing an ACT and thereby increasing the corrosion activity, a large decrease in the average 24h depolarization values can be observed.

The concrete resistivity increases with a factor 3 to 4, when CEM III/A cement is used instead of CEM I cement for a chloride content of 1 m% Cl by the weight of cement. This causes a decrease in the throwing power by an average factor of about two.

An increase in reinforcement density is accompanied by an overall decrease in the mean 24h depolarization values and a decrease in the average throwing power.

As a general conclusion it can be stated that a high concrete resistivity, high concrete chloride content, high reinforcement density and a low source voltage will result in a limited throwing power of an ICCP system. The goal is to protect the reinforcement as far away from the anode as possible without creating overprotection (risk of loss of adherence between the concrete and steel) for the closest reinforcement. This creates a source voltage limitation with a maximum throwing power. Further research is required to determine the exact concrete resistivity, chloride concentration and reinforcement density in which ICCP proves to be an economical and practical solution.

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