



Resistivity of Repair Materials for Concrete Repair Prior to the Application of a Cathodic Protection System

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Abstract. Suitability of repair materials for local concrete repair in combination with a cathodic protection system depends on the compatibility of their electrical resistivity characteristics with the parent concrete. As data on resistivity of repair mortars is very limited, selection of a compatible product is not always possible. In this research, the electrical resistivity of 10 different structural repair mortars was tested at three different environmental conditions (temperature of 20 °C and relative humidity of 60, 80, and 100%) by means of three resistivity test methods: four-point electrode method (Wenner Probe), two-plate electrode method and method with embedded electrodes. In this way, a database is created through which the most suitable repair mortar can be selected for each concrete structure in different environments. The relative humidity (RH) of the environment has a large influence on the resistivity of the repair products: on average, at the age of 91 days, a decrease of the RH of 20% tripled the resistivity of the repair mortars. Furthermore, based on the obtained results it is expected that this effect will be even larger on the long term (e.g. after several years). The two bulk resistivity methods showed comparable results. However, the two-plate electrode method was found to be unsuitable for resistivity measurements of non-saturated mortar specimens. The surface resistivity, measured by the Wenner Probe, was found to be a factor of 4 to 5 times higher compared to the bulk resistivity. The difference can mainly be attributed to the small size of the specimens used in this research.

Keywords: Resistivity · Repair materials · Concrete repair · Cathodic protection

1 Introduction

Cathodic protection (CP) of steel in concrete, either galvanic (GCP) or through impressed current (ICCP), is a widely accepted repair technique to significantly reduce or completely stop corrosion of steel in reinforced concrete structures [1, 2]. Especially when corrosion is induced by chlorides, CP provides a durable and cost efficient repair on the long term [3–5].

Cathodic protection is mostly applied on concrete structures which already have a certain amount of visible damage due to reinforcement corrosion, mostly in the form of cracks, delamination and spalling of concrete. Therefore, before the application of a

CP system, local repair of delaminated concrete is required. The compatibility of repair mortars for local concrete repair with the CP system is a major concern to obtain efficient protection of the steel reinforcement over the whole structure.

The European standard on cathodic protection of steel in concrete, EN ISO 12696:2016 [6], provides certain guidelines concerning the suitability of repair materials in the sense that electrical resistivity characteristics of the repair material should be compatible with the parent concrete. Typically, this is defined as repair materials which have an electrical resistivity within the range of 0.5 to 2 times the mean resistivity of the parent concrete, measured under the same environmental conditions.

The comparison of the electrical resistivity of repair materials and parent concrete of an existing structure is difficult, since the resistivity of the parent concrete is mostly measured by means of an on-site test method, while the resistivity of repair materials is measured in laboratory conditions, mostly with a different test method. Moreover, the environment at which the resistivity is tested is different for the parent concrete and the repair materials.

In this research, the resistivity of 10 different repair mortars was tested at three different environmental conditions (temperature of 20 °C and relative humidity of 60, 80, and 100%) by means of three generally accepted test methods.

This paper discusses the influence of the used test method as well as the relative humidity of the environment on the resistivity of repair mortars.

2 Materials and Methods

2.1 Repair Mortars

Ten different structural repair mortars, commonly applied in Europe for concrete repair, were used in this study. All repair mortars comply with the requirements for a class R4 (structural repair) according to the European standard EN 1504-3 [7] and are suitable to be applied either by hand or by a spraying method.

The repair products are numbered from 1 to 10 in this paper. Repair mortars 1 to 7 are based on a hydraulic binder (denoted as “CC”), while repair mortars 8, 9 and 10 are hydraulic mortars modified by means of polymer additives (denoted as “PCC”).

The main binder type of all repair mortars, except for mortar CC-4, is Portland cement (mostly sulfate resistant). Repair mortar CC-4 on the other hand contains cement replacement (not further specified) and recycled aggregates.

Repair products CC-1 to CC-7 and PCC-10 also contain polymeric fibers. When the type of fiber is specified in the technical data sheet of the product, it is always polyacrylonitrile.

2.2 Mortar Specimens

Two types of mortar specimens were prepared for every repair product to determine the resistivity:

- Mortar prisms with dimensions 200 × 60 × 60 mm

- Mortar prisms with dimensions $100 \times 100 \times 50$ mm containing two embedded stainless steel bars (diameter 6 mm), positioned 50 mm apart

The mortar mix of each repair product was prepared by mixing a predefined amount of water, described in the technical datasheet of the respective product, with the mortar powder by means of a portable handheld paddle mixer. The mix procedure and mixing time as described in the technical datasheet for each product was followed. After mixing, the mortar was brought into the molds and compacted shortly on a vibration table. All mortar specimens were produced in triplicate.

Immediately after casting, the mortar specimens were put in an air-conditioned room at a temperature of 20 ± 2 °C and a relative humidity of at least 95% for 24 h. Subsequently, the specimens were demolded and placed under constant environmental conditions for resistivity testing (see Sect. 90.4).

2.3 Resistivity Measurement Methods

The resistivity of the repair mortar products was measured by three different methods, described in the recommendations of RILEM TC 154-EMC [8] and CUR-Aanbeveling 45 (in Dutch) [9].

A. Four-point electrode method (FPEM) - Wenner Probe (surface resistivity)

The first method to measure resistivity was performed by means of the so-called ‘Wenner Probe’ on the mortar prisms with dimensions $200 \times 60 \times 60$ mm. The Wenner Probe consists of four equally spaced point electrodes which are pressed onto the mortar surface. A current is induced between the two outer electrodes and a potential difference is measured between the two inner electrodes. The ratio between the voltage and the current gives a resistance value, which can be converted to resistivity using a cell constant based on the electrode spacing [10].

The Wenner Probe used in this research is a standard device developed by Proceq called the Resipod meter with an electrode spacing of 50 mm. For each mortar specimen, four resistivity measurements with the Resipod were performed, one measurement on each side (200×60 mm) of the specimen (see Fig. 1a).

B. Two-plate electrode method (TPEM) - bulk resistivity

The second resistivity measurement method was also performed on the mortar prisms with dimensions $200 \times 60 \times 60$ mm, by placing the prisms along their length direction between two stainless steel plates (Fig. 1b). Wet cloths are placed at the contact surfaces of the plates with the prism and a weight with a mass of about 2 kg was placed on top of the upper plate to ensure uniform electrical contact.

The resistance between the two plates was measured by means of an LCR meter at a frequency of 120 Hz. The resistivity was subsequently calculated from the resistance measurement by Eq. (1):

$$\rho = R \cdot A / L \quad (1)$$

where R is the measured resistance (Ω), A is the area of the prism in contact with the stainless steel plates ($60 \times 60 = 3600$ mm²) and L is the length of the prism (200 mm).

C. Embedded electrodes method (EEM) - bulk resistivity

The resistivity measurement method with embedded electrodes is described in the Dutch recommendation document regarding cathodic protection of steel in concrete structures, CUR-Aanbeveling 45 [9]. It is performed by measuring the resistance between two embedded stainless steel bars of the mortar prisms with dimensions $100 \times 100 \times 50$ mm by means of an LCR meter (measurement frequency of 120 Hz), see Fig. 1c.

The resistivity is calculated by multiplying the measured resistance by a cell constant C which depends on the geometry of the mortar prism and embedded electrodes. The cell constant for the specimen geometry used in this research was determined experimentally by filling a mold with the same geometry as the mortar prisms with a 0.01 M KCl solution and measuring the resistance between the electrodes in the same way as for the mortar prisms, i.e. by means of an LCR meter. The conductivity of the 0.01 M KCl solution was measured to calculate its resistivity. Finally, the cell constant was calculated by dividing the resistivity of the solution by the measured resistance.

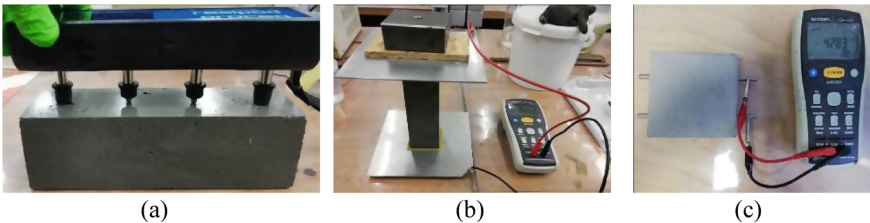


Fig. 1. Resistivity measurement methods: **a** four-point electrode method (FPPEM), **b** two-plate electrode method (TPPEM), and **c** embedded electrodes method (EEM).

2.4 Environmental Test Conditions and Measurement Times

The resistivity of the repair mortars was tested in three different environments at a constant temperature of 20 °C and a relative humidity (RH) of 60, 80, and 100% (immersed in water).

For each test environment, three replicate specimens of each type (see Sect. 90.2) were made for all repair mortars. The resistivity measurements with the three aforementioned methods were performed at 7 different ages of the specimens: at the age of 3, 7, 14, 21, 28, 56, and 91 days.

3 Results and Discussion

3.1 Resistivity in Function of Time

The resistivity of the repair mortars increased with time for all test environments. One example of the evolution of the resistivity in function of time for all tested repair mortars

is given in Fig. 2 where the measurements were performed by the embedded electrodes method (EEM) at test conditions of 20 °C and 80% RH. Similar graphs can be obtained for other test conditions and for measurement with other test methods.

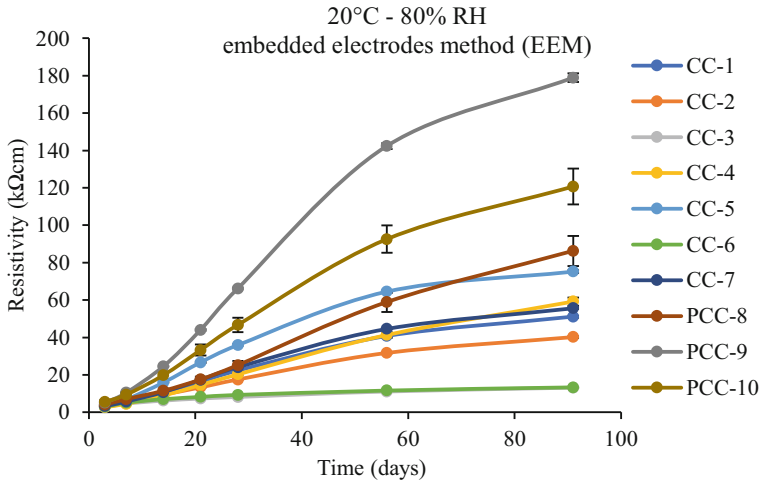


Fig. 2. Resistivity in function of time for all repair products at 20 °C and 80% RH, measured with the method with embedded electrodes (EEM).

In general, there is a large variation of resistivity between the different tested repair mortars: the resistivity of the repair mortar PCC-9, which generally has the highest resistivity in all test conditions, is up to 15 times higher than the repair mortar with the lowest resistivity (mortar CC-6).

Based on the measurements in all test conditions, there are two repair mortars (CC-3 and CC-6) which have a relatively low resistivity compared to the other products, while there is one repair mortar (PCC-9) which has a resistivity that is much higher than all other tested products.

Generally, as can be noticed in Fig. 2, the tested PCC mortars tend to have a higher resistivity compared to the CC mortars. However, this difference is certainly not always significant, for example for mortar PCC-8.

3.2 Influence of Relative Humidity

The relative humidity of the environment has a big influence on the resistivity of the repair products. Figure 3 shows an example of the development of the resistivity in time for repair mortar #1 for storage at different relative humidities.

For storage at 100% RH, the resistivity of the repair products tends to reach a stable value at the end of the testing period, i.e. the resistivity does not increase much anymore between 56 and 91 days for most products. For lower relative humidities, especially 60%, the resistivity keeps increasing significantly after 56 days.

Consequently, the difference in resistivity between the different environments increases in time. Considering all products, the average resistivity increase factor from

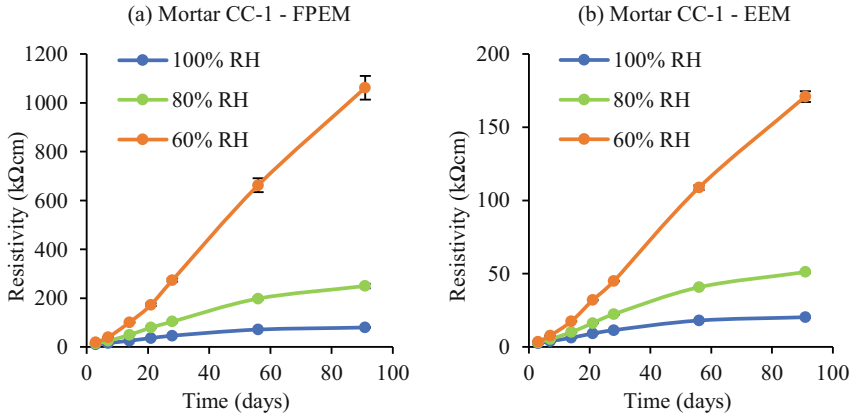


Fig. 3. Influence of the relative humidity (RH) on the development of resistivity in time, measured by **a** four-point electrode method (FP EM) and **b** embedded electrodes method (EEM).

100 to 80% RH and from 80 to 60% RH is very similar. At the age of 91 days, this average factor ranges from 2.6 to 3.3 for all testing methods. Thus, for a decrease of the relative humidity of the environment of 20%, the resistivity of a repair mortar is about 3 times higher at 91 days age. Note that as the difference increases with time, it is expected that this factor will be even higher at larger testing ages.

Figure 4 summarizes the measured resistivity of all repair products at the age of 91 days for the three test conditions (i.e. variation of environmental RH from 100 to 60%) and the three different test methods. The large influence of the environmental relative humidity on the resistivity is also clearly visible in this graph for all tested repair mortars.

3.3 Influence of Measurement Method

Next to the influence of RH, Fig. 4 also shows that there is a difference in the measured resistivity between the different test methods. The bulk resistivity measurement methods, i.e. the two-plate electrode method (TP EM) and the method with embedded electrodes (EEM), mostly show similar results while the resistivity measurements with the four-point electrode method (FP EM) are consistently much higher.

In Fig. 5, the mean ratio of the surface resistivity (ρ_{surface}), measured with the FP EM, and the bulk resistivity (ρ_{bulk}), measured either by the TP EM or EEM, is plotted for the different test environments. As can be seen in the figure, a mean factor between 4 and 5 is obtained for the ratio between surface and bulk resistivity based on all executed measurements. The testing age did not have an influence on this factor.

Despite of the large difference in absolute value of the resistivity between surface and bulk measurement methods, a good correlation between both methods is obtained, see Fig. 6.

The main reason for the higher measured surface resistivity by the FP EM can be linked to the relatively small size of the test specimens used in this research. As has been

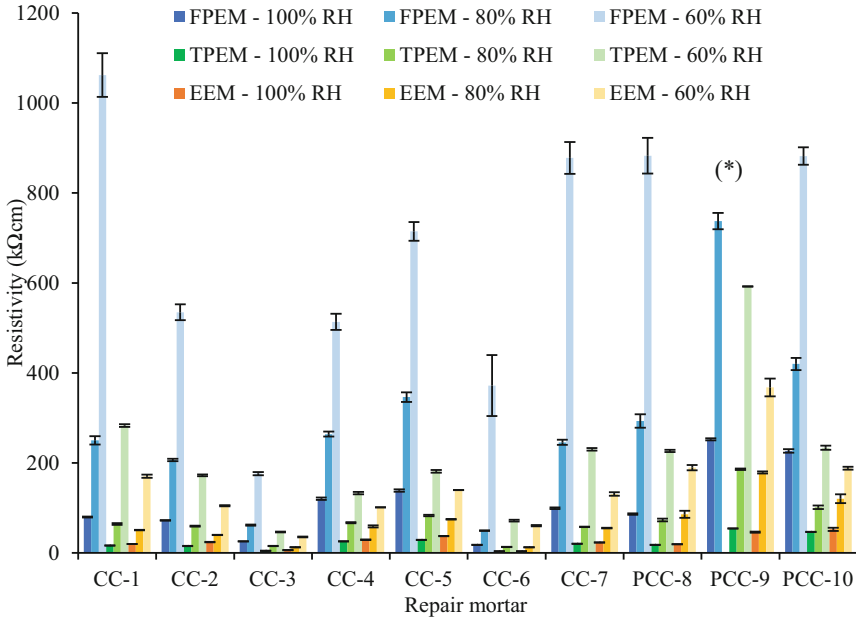


Fig. 4. Resistivity of all repair products at 91 days age. (*) The resistivity of repair mortar #9 at 60% RH could not be measured by the FPEM as it was higher than the measurement range (>2000 kΩ cm) of the test device.

established in literature [10–12], the measurement of surface resistivity by means of the FPEM (Wenner Probe) on small scale laboratory specimens will give an overestimation of the true resistivity of the material due to the fact that a semi-infinite medium is taken into account in the (automatic) calculation of the resistivity. Therefore, the measurements by the FPEM method on the specimens in this research should be considered as an apparent resistivity, not the true resistivity of the material.

Lastly, it should be noted that at a high relative humidity (80 or 100%) the results of the resistivity measurement by both bulk resistivity methods (TPEM and EEM) show very good agreement. At a relative humidity of 60% however, the agreement between both methods is worse, in the sense that the TPEM always leads to higher resistivity values (see Fig. 4). This can be attributed to the fact that the resistivity measurements by means of the TPEM were unstable at a lower RH. The measured resistance values decreased over time during execution of the measurement. An example of this is given in Fig. 7 for the measurement at 60% RH at an age of 56 days.

The effect of decreasing resistance during the measurement was more pronounced for increased age of testing. The measurement was stopped after about 5 to 10 min until a more or less stable measurement value was obtained. However, probably the measured resistance would have slowly decreased further if the measurement was continued. This effect was also noticed for the specimens stored at 80% RH, but less pronounced.

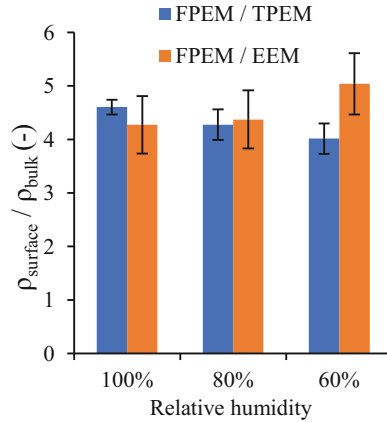


Fig. 5. Ratio of surface and bulk resistivity measurements.

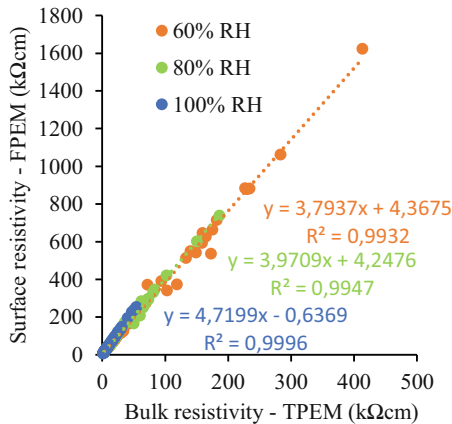


Fig. 6. Correlation between surface and bulk resistivity measurements.

Therefore, the TPEM was found to be unsuitable for measurement of resistivity of mortar/concrete specimens which are stored at low RH or, more generally, unsuitable for unsaturated mortar/concrete specimens due to the long required measurement time.

A possible way of avoiding this would be to attach electrodes by means of a conductive adhesive layer to each sample separately, instead of using the two plates with a wet cloth at the contact surface with the specimens.

4 Conclusions

Ten different structural repair mortars, commonly used for concrete repair in Europe, were tested in this research on their electrical resistivity in order to evaluate their possible use for concrete repair in combination with the application of a cathodic protection system.

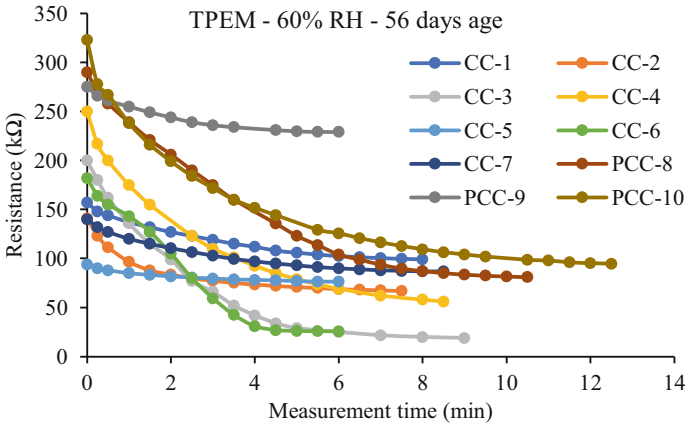


Fig. 7. Example of decreasing resistance during measurement with the two-plate electrode method (TPEM).

Repair mortar specimens were prepared and stored at three different test environments at 20 °C and varying relative humidity (RH) of 60, 80, and 100% for a period of 91 days. The resistivity of the mortar specimens was measured at regular time intervals by means of three commonly used test methods for both bulk and surface resistivity.

Two out of the ten tested repair mortars have a very low resistivity compared to the other products, while there was one product (PCC repair mortar) which has a resistivity that is much higher than all other tested products.

A clear dependency of the resistivity on the relative humidity of the environment was noticed, in the sense that the resistivity is lower for at a higher RH. At 100% RH, the resistivity nearly reached a stable value after a testing period of 91 days for most products, while at lower relative humidities the resistivity kept increasing. Especially at a RH of 60% there was still a large increase in resistivity from 56 to 91 days. In order to reach a stable resistivity at this environment, a much longer test period would be required.

Comparable results were obtained with both bulk resistivity test methods in most cases. Only in the case of a relatively low RH of the environment (unsaturated specimens), the two-plate electrode method was found to unsuitable due to unstable measurement readings.

By means of the surface resistivity method (four-point electrode method or Wenner Probe), the obtained resistivity was on average 4 to 5 times higher compared to the bulk resistivity methods. The higher measured resistivity can most probably be linked to a geometrical factor or correction factor which should be applied to account for the effect of the small sample size of the specimens used in this research. However, this shows that it is very important to mention the measurement method and specimen size, next to the age and storage conditions, when reporting resistivity measurements.

Based on the measurements performed in this research, a database is created of the resistivity of commonly used repair mortars at different environmental conditions

which makes it possible to choose the most suitable repair mortar for local concrete reinstatement prior to the application of a cathodic protection system.

In further research, the influence of temperature on the resistivity of repair mortars will be investigated and modelling of the resistivity in function of time, relative humidity and temperature will be performed in order to be able to predict the resistivity of other repair products under specific environmental conditions.

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