Mechanical, electrical and microstructural properties of cementbased materials in conditions of current flow

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Summary

Corrosion in reinforced concrete structures is not only induced by the penetration of aggressive substances (e.g. chlorides and/or CO₂) but also influenced by stray currents. Further, the degradation mechanisms in reinforced cement-based systems due to the combined effect of stray current and chloride penetration have been a serious problem in civil engineering for many years. In the case when reinforced concrete is exposed to the above factors for long-term periods, service life will be reduced. With respect to the effects of stray current, the magnitude of the corrosion damage is directly related to the current density at the point of departure and the time over which the current flows. The higher the current density, the greater the resultant corrosion damage to the structure. High levels of DC stray current would dramatically decrease mechanical properties, which could be in parallel to increased chloride diffusivity and decreased threshold of chloride concentration with respect to corrosion initiation. Stray currents will therefore produce microstructural alterations, resulting from modified electrical properties of the concrete bulk matrix, which in turn will influence the corrosion resistance properties.

This work reports on the influence of DC current, flowing through mortar specimens, on bulk matrix properties. The investigation presents a comparative study of mechanical properties (e.g. compressive strength), electrical resistivity and microstructure (porosity, pore size distribution) of mortar under DC current, compared to mortar in rest (no current) conditions. Additionally, numerical simulation of the stray current distribution is performed, meant to serve as a basis for further elaborated modeling of the level of current density that would exert significant microstructural alterations in a bulk cement-based matrix.

1. Introduction

Stray current is a current flowing in an electrolyte (soil, water) that arises from metal conductors in these media and is produced by electrical installations. It can be the result of direct current (DC) or alternating current (AC), predominantly with a frequency of 50 Hz (public electricity supply) or 162/3 Hz (traction power supply). There are a number of sources of undesirable stray currents, including foreign cathodic protection installations, DC transit systems such as electrified railways, subway systems and streetcars, welding operations, and electrical power

transmission systems. With respect to steel corrosion, apart from environmental conditions and other factors that can significantly compromise the corrosion resistance of a reinforced concrete structure, stray DC and/or AC currents can be corrosion-initiating or corrosion-contributing factors as well. Stray currents tend to enter a buried reinforced concrete structure in a certain location and leave it in another. It is where the current leaves the structure that severe steel corrosion is expected. Stray direct currents are known to be much more dangerous than stray alternating currents [1]. In a few extreme cases, severe structural damage was observed and recorded as a result of stray current leakage [2-4]. The effect of stray currents has mainly been investigated in terms of steel corrosion: the mechanisms of corrosion initiation on initially passive reinforcement and the effects on already corroding reinforcement have been both reported [2,4]. The influence of several accompanying factors such as: cement type (Ordinary Portland and blended cements), type of current (AC or DC), current density, the presence of interruptions in the current circulation, and coexisting chlorides were also reported [2-6]. For example, some studies showed that high levels DC would dramatically decrease bond strength within a few months of current flow at measured current density levels between 1 and 10 A/m² [1, 7-10].

Numerical simulation for the influence of stray current and modeling the performance of a reinforced concrete structures with this regard are also reported ([11-23]), emphasizing on determination of the corrosion initiation and propagation period due to chloride diffusion. Clearly, the degradation of cement-based systems due to stray current and chloride penetration followed by corrosion has been largely recognized as a serious problem in civil engineering for many years. However, the majority (if not all) of related works are not reporting any in-depth investigation on the microstructural properties of the bulk cementitious matrix i.e. most of the reported related studies are with respect to corrosion issues mainly.

Since microstructural properties determine mechanical properties, as well as chloride diffusivity and therefore corrosion initiation, the alterations of the cement-based bulk matrix can not be neglected and need deeper investigation is needed in order to properly predict the behavior of reinforced concrete in the above discussed environments. This work emphasizes on mechanical properties and microstructural characteristics of plain mortar, subjected to DC current flow. The objective was to provide an initial outlook and preliminary results on the influence and consequence of stray currents in non-reinforced cement based materials. Numerical simulation of the stray current distribution was performed and coupled to the bulk matrix properties, which will further serve as a basis for predicting stray current density distribution and resulting electrical and microstructural properties of cement-based systems.

2. Experimental Materials and Methods

2.1. *Materials:* The studied specimens were mortar cubes of 40 mm \times 40 mm \times 40 mm (Fig.1), cast from Ordinary Portland cement (OPC CEM I 42.5N), water-to-cement ratio of 0.5 and cement-to-sand ratio of 1:3.



Figure 1: Experimental set-up for group S (Stray current regime)

Two groups of specimens were monitored: group R – control group (no current flow involved) and group S – "stray current" group (mortar cubes subjected to current flow throughout the experiment). Both groups were tested from 1 day until 84 days in two replicate series of tests A and B (total of 128 cubes). Compressive strength measurements were performed for both series; series A was investigated for hydrated water content and microstructural properties, whereas series B was additionally monitored for electrical resistivity and conductivity of the environmental medium. The mortar cubes from groups R and S (in both series A and B) were half immersed in tap water (aqueous environment was necessary to ensure electrical conductivity for the S group, whereas an accurate comparison requires equal environmental condition for R group). After casting and prior to conditioning, the specimens were cured in a fog-room (98% RH, 20°C) for 24 hours; after mould removing they were positioned in the relevant containers, Fig.1 (without – group R and with – group S current flow in the medium).

2.2. Current regime: A simulation of stray current was achieved by injecting a DC current at the level of 10 mA/m², Fig.1 (a negative and a positive terminal were connected to a 25 V source and the desired current density was adjusted via additional resistors in the circuit) i.e. the cubes in the container are positioned in aqueous environment, where controlled DC flows throughout the experiment for 84 days.

2.3. Methods

2.3.1. Standard compressive strength.

Standard compressive strength tests were performed on 40×40×40 mm mortar cubes at the hydration ages of 24h, 3, 7, 14, 28, 56 and 84 days. Within the two replicate test series (A and B), three replicate specimens were tested per hydration age.

2.3.2. Mortar electrical resistivity and water conductivity.

Concrete electrical resistance was recorded via a 2-pin method: current was applied and voltage was measured across a sample with dimensions of 40×40×40 mm; conversion to electrical resistivity was performed using the well known equation: $\rho = R.A/I$, where ρ is the resistivity in Ohm.m, R is the resistance in Ohm, A is the cross-section in m^2 , and I is the length in m. Conductivity measurements for the testing environment were performed using conductivity meter by immersing a probe into the water solution. The SI unit of conductivity is S/m and refers to 25 °C (standard temperature).

2.3.3. Microstructural analysis.

Microstructural analysis was performed at each of the above mentioned hydration ages for specimens from both test series A and B. For the specimens in series A (both R and S groups), the sample preparation followed well defined and accepted procedures of sample cutting, vacuum impregnation, grinding, polishing etc. which were after ceasing cement hydration in liquid nitrogen and freeze-drying of the samples to constant weight before impregnation [24-25]. For the specimens in series B, the sample preparation followed the general procedure without ceasing cement hydration (i.e. after cutting, the specimens were vacuum dried and vacuum impregnated; analysis took place immediately after sample preparation that is on the relevant hydration age of interest). Scanning electron microscopy (using environmental SEM (ESEM Philips XL30)) and image analysis (OPTIMAS software) were used to determine the pore structure parameters of the specimens. The physical size of the reference region of each image is 226 µm in length and 154 µm in width, with a resolution of 0.317 µm/pixel (corresponding to a magnification of 500x); the pore size considered for image analysis is larger than 0.317 µm. In order to quantify the pore structure, image analysis was performed on an average of 25 locations per sample. The image analysis in this study complies with the generally used methodology for pore structure and phase distribution analysis of cement based materials, implementing mathematical morphology and stereology approaches [24-30].

2.3.4. Mercury intrusion porosimetry (MIP).

Sample preparation for MIP analysis followed the aforementioned for test series "A" generally accepted procedure [26, 29]. The MIP tests were conducted by using Micrometritics Poresizer 9320 (with a maximum pressure of 207 MPa) to determine the porosity and the pore size distribution of the specimens. The Washburn equation [31] was used to calculate the diameter of pores intruded at each pressure step, which is shown as: $D=-4\gamma\cos\theta/P$, where D is the pore diameter, γ is the surface tension of mercury, θ is the contact angle between mercury and the pore wall and P is the applied pressure. The surface tension of mercury was 484 ×10⁻³ N/m and the contact angle was 130°. The measurement was conduct ed in two stages: the first stage was at low pressure: from 0 to 0.0036 MPa and the second stage was at high pressure running from 0.0036 to 210 MPa. According to Washburn equation [31], the pore size range detected is from 350 µm to 0.007 µm.

2.3.5. Chemical analysis for hydrated water and ion concentrations in the conditioning water.

Alkali ions concentrations in the tap water in the containers at the beginning of the test and after 28 days were determined by plasma spectrometry using Inductive Coupled Plasma spectrometer (ICP-AES). The hydrated water per certain hydrations age (test series A) was determined according NEN 5931 (which is a standard loss of ignition test).

2.3.6. Numerical simulation.

Numerical simulation of stray current was performed to obtain potential and current density distribution in the mortar cubes. Further, the current density depends on the electrical resistivity/conductivity of the mortar and the external aqueous medium. The governing equations for the stray current model are as follows:

$V.J = -\partial \rho / \partial t$	(1
I – E	()

$$\begin{aligned} F &= O E \end{aligned} \tag{2} \\ E &= -\nabla V \end{aligned} \tag{3}$$

$$D = \mathcal{E}_o \, \mathcal{E}_r \, E \tag{4}$$

where equation (1) gives the relationship between current density J (A/m²) and charge density ρ (C/m³) (continuity equation). For steady current (DC) as used in this

experiment, the charge density does not change with time so that the divergence of the current density is always zero (∇ . J=0); equation (2) known as Ohm's Law for conduction current that gives relationship between current density J (A/m²) and electric field E (V/m) where the constant is proportionality called electrical conductivity (S/m); equation (3) gives relationship between electric field E (V/m) and gradient of a scalar potential V (Volt); equation (4) gives relationship between electric flux density D (C/m²) and electric field E (V/m) that describe the interaction between charged material with relative permittivity ε_r and vacuum permittivity ε_0 . D is related to the charge densities associated with this interaction, while E is related to the forces and potential differences. These equations were implemented in the finite element method (FEM) of COMSOL Multiphysics V 4.2 software in the AC/DC module [32].

3. Results and Discussion

3.1. Chemical analysis – hydrated (chemically combined) water.

The hydration mechanisms in cementitious materials are of generally high complexity, where water plays a decisive role. Being the main source for mass transport in the cement-based porous structure, water can be classified into different forms (chemically combined, interlayer, absorbed, free (capillary) water) [33]).



Figure 2: Hydrated water at 1-84 days of ages for R and S specimens, series A.

Chemically combined (hydrated) water is part of the hydration products, and could be released only with decomposition of hydrates. The hydrated water is further related to the hydration rate of the cement-based material i.e. can approximate the degree of cement hydration, hence is related to electrical resistivity and ease of ion transport.

Relevant to the present study, the amount of hydrated water at certain time intervals was investigated as an indication of possibly different hydration mechanisms when current flow is involved (as in group S) compared to control conditions (group R). Figure 2 presents the amount of hydrated water (in percent per dry cement weight) for both groups R and S (test series A) in the time interval of 1 day – 84 days. Compared to group R, initially similar or higher values of hydrated water content were recorded for group S at earlier stages (1, 3 and 7 days), whereas a decreasing trend is evident after 14 days of age. In an advanced stage of the hydration process, diffusion processes are the limitation ones and these are solely relevant for specimens group R. As for specimens group S, the hydration process is determined by diffusion but also migration due to an accelerated ion and water transport under current flow. Therefore, the current flow for group S initially accelerates cement hydration. The effect shows a reversed trend on later stages (14-84 days), which is denoted to the simultaneous contribution of current flow and concentration gradients

(tap water as external environment) on cement hydration. Consequently, more pronounced alterations in microstructural and electrical properties, further resulting in a drop in compressive strength was recorded for specimens S, compared to the control cases (specimens R), which will be further discussed.

3.2. Compressive strength

Compressive strength is an engineering property of cement-based materials, reflecting mechanical performance. Generally, with cement hydration (i.e. with time and if no other external factors are present), the compressive strength increases. The development of the internal microstructural characteristics, resulting from chemical and physico-chemical phenomena related to cement hydration, determine the mechanical performance of cement-based materials.



Figure 3: Compressive strength measurements for control R and "stray current" S groups from 1 day to 84 days of hydration age in the two replicate series of tests: a) series A and b) series B

Figure 3 presents the development of compressive strength for both control (R) and "stray current" (S) groups from initial conditioning (24h after casting) until the end of the test (84 days). As aforementioned, both groups R and S were tested in duplicate i.e. compressive strength was recorded for two equally designed (in terms of mortar mixture and conditioning) test series A (Fig.3a) and B (Fig.3b). Slightly different values between series A and B were recorded in the beginning of the test (24h to 14 days), which is acceptable, considering the high level of structural heterogeneity of cement-based materials.

The common outcome, observed in both test series is the lower compressive strength for groups S, compared to group R at later hydration stages. For the test series A (Fig.3a) the derived compressive strength values are well in line with the previously discussed amounts of hydrated water: similar or higher percentage of hydrated water for group S at 1, 3 and 7 days (Fig.2a) correspond to increasing compressive strength (Fig.3a). After 14 days and further with conditioning, the percentage of hydrated water for specimens S was lower (Fig.2a), corresponding to constantly lower compressive strength (Fig.3a). For groups R and S in the tests series B (Fig.3b), again lower compressive strength values were recorded for the specimens under stray current condition (group S), after 14 days of age and maintained lower until 84 days of age. The compressive strength values for groups R, although maintained higher than these for groups S, did not significantly increase as expected with time of cement hydration, but were rather constant (after 28 days of age) or slightly decreased at the end of the test (Fig.3b). The observed behavior is

denoted to microstructural changes in the bulk mortar matrix, which will be presented in what follows.

3.3. Microstructural properties

The development of the pore structure in hardening cementitious materials is fundamental to their mechanical behavior. It influences ion and water transport and their interaction as well as the diffusion characteristics of the bulk matrix.



Figure 4: Porosity (a, b) and pore size distribution (c, d) for groups R and S in both test series A and B at earlier stages (24h to 14 days).

Previous studies on the influence of electrical current within cathodic protection applications revealed that a current flow in the range of 5 to 20 mA/m² brings about densification of the concrete bulk matrix on one hand, but also leads to enlargement of the interfacial transition zones after more than 120 days of hydration (ITZs) [34,35]. The electrical current flow involved within this investigation (10 mA/m²) was therefore expected to affect the material structure (including pore structure) of the hereby studied mortar specimens. Figures 4 and 5 depict the calculated porosity and pore size distribution for specimens R and S in both tests series A and B. Fig. 4a) depicts a comparison of the porosity values for specimens R and S, series A at the earlier stages of 24h, 3d, 7d and 14 days. Fig. 4b) presents the porosity values for specimens R and S, series B at the stages of 7 and 14 days. Figs. 4c)d) show the corresponding differential curves and critical pore size. Both S and R specimens have equal pore structure characteristics for the first time interval (24h) since current regime was still not relevant for specimens S. Initial densification of the matrix at 3 days and 7 days was observed for specimens S in both test series A and B (compare 7 days age in Figs. 4a) and 4b)). At 14 days of age, porosity and critical pore size are

similar for both S and R specimens (5.6% in series A and 6.7% in series B - Figs. 4a) and b), 14 days). The initial densification of the matrix for specimens S is attributed to accelerated ion and water transport due to the presence of electrical current flow, consequently increased cement hydration. This outcome is in line with the recorded amounts of hydrated water (Fig.2) where the initial stages for specimens S show higher percentage of hydrated water content.



Figure 5: Porosity (a, b) and pore size distribution (c, d) for groups R and S in both test series A and B at later stages (28 and 84 days).

At the stage of 28 days of cement hydration (Fig.5), an opposite trend of microstructural development was observed for S and R specimens (in both series A and B) i.e. porosity was increased to ~ 12% for group R and ~ 14% for group S. This observation is supported by the amounts of hydrated water content (Fig.2), which show a decreasing trend from 14 to 28 days for specimens S and is also in line with the lower compressive strength values (Fig. 3). At 84 days of age, porosity for both S and R specimens is even higher: ~17% for specimens S and ~14% for specimens R (Fig.5 a, b)

A general perception for a cement-based material is that porosity will decrease with time and with prolonged cement hydration respectively. This, however, is not always the case. Microstructural alterations and Ca-leaching for example would affect the matrix. For the case of this experiment (in both series A and B and for both specimen groups S and R), calcium (and sodium, potassium ions) leaching are a result of concentration and pH gradients between the cement-matrix and the external (tap water) environment. Except in increased conductivity of the test solutions (Fig.6) in which the mortar cubes were immersed, the leaching process results in coarsening of

the pore structure, which is more pronounced for specimens S due to the applied current flow.



Figure 6: Electrical conductivity of the aqueous environment for both groups R and S with time of conditioning and Na⁺, K⁺ and Ca⁺⁺ concentration at the beginning and end of the tests

Compared to the control specimens R, the pore structure of S specimens is initially (3 to 14 days), with reduced porosity and critical pore size Fig.4a), whereas higher porosity (and larger critical pore size) was observed at the stage of 28 and later ages, Fig.5a). It can therefore be concluded that stray current initially affects the bulk matrix properties in terms of matrix densification; whereas a coarser pore structure was observed towards the end of the test as a result of simultaneous stray current and leaching effects.





Figure 7: Porosity and pore size distribution obtained from MIP results for 28 days



As seen from Fig.6, the electrical conductivity of the environmental medium is higher for specimens R, compared to specimens S. Sodium and potassium concentrations are also higher, whereas calcium concentration is lower, compared to the environment of group S (no absolute values are claimed, just a comparison of initial and end of test concentrations are presented). Since coarsening of the pore structure for both S and R groups was recorded starting at 28 days of age, apparently the initially denser matrix for specimens S results in maintaining higher concentration of alkali ions in the pore water (i.e. in the matrix). Calcium leaching is, however, more pronounced compared to the R specimens S (17.4 % porosity), compared to the matrix of specimens R (14 % porosity) at the stage of 84 days.

The microstructural data, derived from image analysis are well supported by MIP tests. Figs. 7 and 8 depicts the results for 28 days and 84 days, where clearly seen is that the matrix of specimens S is coarser than that for specimens R for both hereby depicted hydration ages. Considering that the image analysis can derive information for the pore system in the range of the rectangular area in Figs. 7 and 8, the correlation of data from MIP (Figs.7 and 8) and image analysis (Figs. 4 and 5) gives a more complete information for the alterations in the pore system for both S and R samples.

Analysis of porosity and pore size distribution (Figs. 4, 5) reveal initial densification of the matrix for group S, supported by higher hydrated water content (Fig. 2) and increasing compressive strength (Fig.3). On later stages, current flow induces coarsening of the cement-based matrix (Figs. 4,5,7,8) and decrease or stabilization of compressive strength values at lower values, compared to the control group R (Fig. 3). The responsible mechanism is the coupled action of current flow and calcium leaching (which is in addition to altered cement hydration in the presence of current flow).

4. Numerical simulation and correlation of results

The electrolytic path in cement-based systems is dependent on the kinetics of ions/water transport mechanisms, the latter affected by porosity, pore size distribution and pore connectivity. The development of the pore structure further influences the mechanical properties, shrinkage behavior, diffusion properties and controls durability [36-37]. Electrical resistivity (conductivity respectively) is another property of a cement-based material, related to the ability of the matrix to resist the passage of electrical current. Electrical resistivity is fundamentally related to the permeability of fluids and diffusivity of ions through porous materials such as mortar/concrete. Resistivity monitoring for the S and R specimens was performed for the total duration of the test at each previously discussed hydration age. Figure 9 depicts the derived electrical resistivity values for both groups S and R at 3 days (Fig.9a, b) and 84 days (Fig. 9c, d). The plots in Fig. 9 additionally depict information for the relevant hydration age as follows: the average compressive strength: compressive strength per cube tested (shaded columns); porosity and pore size for the time interval; and the current density that flows through each cube (for the S specimens), including the cumulative current density for the cubes that were tested for compressive strength. Upon correlating all depicted data in Fig. 9, the following can be stated:

- electrical resistivity increases with time for both S and R specimens, which is more pronounced for the R specimens;
- the electrical resistivity for specimens S is on average higher than that for specimens R at earlier hydration stages (e.g. 3 days, Figs.9 a)b); At the latest time interval (84 days, Figs.9c,d) electrical resistivity for the S cubes is lower (in the range of 8 9 Ohm.m) compared to the R cubes (in the range of 10 16 Ohm.m);
- previously discussed were the lower compressive strength values for specimens S, compared to specimens R with time of conditioning; with respect to correlating mechanical and electrical properties, it can be seen that generally the higher the current density per cube, the lower the compressive strength (Fig.9a). However, no straightforward relation can be made, since microstructural alterations play an important role as well;
- although the average current density per cube decreases with time (which is with increasing the electrical resistivity of the matrix, Fig. 9a and Fig.9c), the cumulative current density, passing through each cube increases with time – Fig. 9c);



Figure 9: Electrical resistivity and current density for S specimens per cube at the hydration age of 3 days (a) and 84 days (c); electrical resistivity for R specimens per cube at 3 days (b) and 84 days (d).

- the electrical resistivity values for specimens S increase with time (although in a lower range than these for specimens R), whereas porosity and pore size distribution increases i.e. there isn't a straightforward correlation of electrical resistivity and microstructural properties;
- considering all experimental data (previously discussed and partly summarized in Figs.9), a numerical simulation for the current density per cube can be performed and further correlated to the development of mechanical and microstructural properties.

Figure 10 presents an example for the numerical simulation of current distribution for the specimens S (as previously specified, all cubes were half immersed in tap water for the total duration of the test; at each time interval there are missing cubes in the plots – these were the cubes taken out for all relevant tests per hydration age). At the beginning of the test (1 day, Fig.10a, c), the level of current density in the immersed (bottom) sections of the cubes (Fig. 10c) almost equals the current distribution in the external aqueous environment, whereas lower current densities are relevant for the top (higher resistant) sections of the cubes (Fig.10a).



Figure 10: Stray current model for 1 day (a, c), 3days (b, d), 28 days (e) and 56 days (f)

After 3 days of conditioning i.e. with time of cement hydration, densification of the matrix and developing of mechanical strength, lower current density flows through the highly resistive top sections of the cubes (Fig.10b); the bottom sections also become more resistive to current flow (Fig.10d). At later stages (28 and 56 days, Fig.10e,f), the current density per cube decreases for both top and bottom sections of the cubes, maintaining lower values for the bottom sections.

The source of electrical current throughout the experiment is current controlled (not voltage controlled), meaning that the level at which the 10 mA/m² DC current is supplied is constant. The difference in the actual current density per cube is therefore determined from the difference in electrical and microstructural properties of the cement matrix with time of conditioning. In other words, although all cubes theoretically receive the same amount of current, the accumulated current density is different per cube and this is well visible from Fig. 10. For example at 3 days of age (Fig. 10d) the bottom sections of the cubes in the upper part of the experimental set-up (indicated with arrows in Fig.10d) "receive" higher current density, compared to those in the bottom part. At 28 days some cubes are more resistant to current flow (arrows in Fig.10e), compared to others. Gradually (e.g. 56 days, Fig.10f), the immersed bottom part of the cubes becomes more and more resistive to current flow.

The model can thus provide the current density values per cube with time of conditioning. Further, the level of current density can be correlated to microstructural and mechanical properties for each cube. The end result would be a correlation of current density and bulk matrix properties i.e. the influence of current flow on cement-based matrix can be evaluated and further extrapolated to predict performance within longer time intervals.

Figs 11 and 12 depict some of the derived dependencies, using the current density values derived from the model in correlation to the experimentally derived porosity values per cube and per hydration age. Figure 11 presents the porosity values for both S and R specimens, the actual cumulative current, passed through these same cubes for the case of specimens S (solid symbols) and the hypothetic (modeled) current that would correspond to the specimens R (open symbols). The cumulative current increases with time of conditioning which initially causes densification of the matrix for specimens S (due to increased ion and water transport and higher hydration rate, as discussed in the previous sections and supported by the relevant experiments). The electrical properties for specimens R are similar to those for specimens S and therefore the hypothetic current density for specimens R is the same as the real current density for specimens S until 14 days of hydration. Further, the current density for specimens S induces increase in porosity, whereas the lower hypothetic current density values for specimens R would exert lower porosity values, as actually experimentally derived.



Figure 11: Correlation of porosity for specimens S and R and cumulative current density per hydration age (actual current density for specimens S and hypothetic values for specimens R as calculated by the stray current density model).

Fig. 12 depicts the average current density, derived by the model in the middle cross section of each cube that was actually subjected to microstructural analysis. Similar trends as for the cumulative current was observed between the actual values for cubes S and the hypothetic values for cubes R.



Figure 12: Correlation of porosity for specimens S and R and average current density per tested cross section and hydration age (actual current density for specimens S and hypothetic values for specimens R as calculated by the stray current density model).

More importantly, it can be concluded that indeed, an initial influence of the current flow results in densification of the matrix in specimens S (24h to 14 days), whereas within further conditioning the average current density per cube decreases (determined by increased electrical resistance due to cement hydration) but higher porosity levels are recorded (28d to 84d). In other words, counteracting mechanisms are involved: on one hand the electrical current initially induces positively altered cement matrix due to enhanced water and ion transport; on the other hand and at later stages, the enhanced ion transport results in enhanced calcium leaching and thus leads to a more pronounced coarsening of the matrix. In order to separately evaluate the relevant mechanisms, the next step in this investigation will be to perform these experiments in different (than tap water) environment (e.g. sat. Ca(OH)₂) or in sealed conditions. This will clarify the separate contribution of electrical current flow and cement hydration. Further, these next experiments will be performed for longer time intervals in order to evaluate the potential influence of electrical current on interfacial transition zones. By all means, it can be clearly stated that the numerical simulation of current density distribution, validated by real experimental data, can certainly bring clarity in evaluating the influence of stray current on mechanical, electrical and microstructural properties of cement-based materials. Moreover, a threshold for positive/negative influence of current flow on bulk matrix properties can be derived.

5. Conclusions

The paper discussed microstructural, mechanical and electrical properties of mortar specimens in conditions of current flow, compared to control (non-current) conditions. Numerical simulation for current density distribution was performed and validated with the experimentally derived results. The following conclusions can be summarized:

- Electrical current flow (at the level of 10 mA/m²) through the mortar matrix initially (24h to 14 days) accelerates cement hydration, resulting in higher percentages of hydrated water content and denser bulk matrix due to reduced porosity and critical pore size;
- Compressive strength and electrical resistivity for the mortar, subjected to electrical current flow (group S) increases with time, but is maintained lower, compared to these values for the control (group R) mortar matrix;
- At later conditioning intervals (14 to 84 days of age), the electrical current brings about microstructural alterations in terms of coarsening of the bulk matrix. Since a more open pore structure was also observed for the control cases, a contributing mechanism was calcium leaching in the testing environment. The difference in porosity and pore size distribution between specimens S and specimens R at the latest time interval of 84 days, higher for the former and lower for the latter cases, are attributed to the influence of current flow.
- Apart from diffusion, increased ion and water migration when current flow is involved initially have a positive effect on cement-based properties; however, the enhanced water and ion transport on later stages induces negative alterations, which correspond to reduced mechanical and electrical properties, that in turn would ease aggressive ions transport (if any) and reduce corrosion resistance if reinforcement was present.
- Further tests will be performed in suitable external environment and/or conditions in order to separately evaluate the relevant mechanisms.

6. References

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