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Mechanical, Electrical and Microstructural Properties of Cement-Based Materials in Conditions of Stray Current Flow

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Abstract

This investigation presents a comparative study on mechanical properties, electrical resistivity and microstructure of mortar under DC current, compared to mortar in rest (no current) conditions. Monitoring was performed from 24h after casting until 84 days of cement hydration. A current density level of 10 mA/m\textsuperscript{2} was chosen as a simulation regime. It was found that the DC current exerts microstructural changes in the bulk mortar matrix and thereby affects electrical properties and mechanical performance. Whereas the latter were slightly influenced, the former were modified to a more significant extent; the current flow was found to cause initial densification of the bulk matrix at earlier stages (until 14 days of age), whereas coarsening of the material was observed after 56 and until 84 days of cement hydration. Additionally, numerical simulation of the stray current distribution is performed, meant to serve as a basis for further elaborated modelling of the level of current density that could exert significant microstructural alterations in a bulk cement-based matrix.

1. Introduction

Stray current is a current flowing in an electrolyte (soil and water respectively) 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). The flow of stray current has to be avoided or minimized not only because of safety concerns, but also because of the possible negative effects on buried materials and structures. In order to minimize these effects and risks of physical and assets damages, standards and safety regulations, e.g. EN50122-1 1997, EN50122-2 1999, EN50122-3 2010, IEC61439, specify the maximum permissible electrical current related to DC electrified railways, traction systems, earthing and returning circuits, interfaces between AC and DC installations. EN50122-2 stipulates maximum values of 60 V for DC currents and 25 Vrms for AC currents for the accessible (step) voltages as function of time during an electrical failure of public transport equipment, ancillary equipment (fixed installations) and electronic applications for railways. EN50122-3 states lower maximum permissible voltages of 25 V. Except the above general possibilities for stray current flow, there are a number of undesirable stray current sources, including foreign cathodic protection (CP) installations, DC transit systems, subway, streetcars, welding operations, electrical power transmission systems. Whereas safety regulations are strictly monitored, the materials’ properties on microstructural levels are not as widely studied and reported.

Regarding steel and reinforced concrete structures, apart from environmental conditions and other factors that can significantly compromise corrosion resistance, stray DC and/or AC currents can be corrosion-initiating or corrosion-contributing factors (Bertolini et al. 2007, Wu et al. 2011, Chen et al. 2011, Yang et al. 2008, Tang et al. 2010). Stray currents tend to enter a buried steel or reinforced concrete structure in a certain location, which becomes a cathodic site and hydrogen gas is produced at this entering point (Kish 1981). The current leaves the structure on another location, which becomes anodic and corrosion initiation or severe corrosion propagation occurs (Bertolini et al. 2007, Wu et al. 2011, Chen et al. 2011, Yang et al. 2008, Tang et al. 2010, Kish 1981, Merrick 1994).

With respect to corrosion initiation and propagation, including negative effects of stray currents but also as a controlling factor for stray current distribution, electrical resistivity is a parameter with high significance. In fact,
the principle to deal with stray current distribution in the engineering practice is related to adjusting electrical resistivity levels (Whiting et al. 2003). For reinforced concrete structures the ionic conduction path is essentially the pore network of the concrete bulk matrix. Resistivity values of less than 50 Ohm•m can support a rapid steel corrosion process; resistivity for Ordinary Portland cement (OPC) concrete for air-dry condition and w/c ratio of 0.5 is reported to be 23 Ohm•m (Whiting et al. 2003, Brown 1980). High resistance to the passage of current, or dry condition, are unable to support ionic flow, hence corrosion is minimal if occurring at all (Brown 1980). Corrosion can be limited by increasing concrete resistivity to above 200 Ohm•m (Trepmper et al. 1958, Vassie 1980, Alonso et al. 1988). For aggressive environments and/or actively corroding steel, concrete resistivity needs to be higher than 500 Ohm•m - 1000 Ohm•m (Broomfield et al. 1993, Broomfield 1997) in order to account for reduced or minimum corrosion rates. Clearly, electrical resistivity is a parameter, influencing both corrosion phenomena and stray current distribution and as such needs constant attention. Logically, if any external influence affects the electrical or microstructural properties (and vice versa) of a concrete/reinforced concrete structure, not only corrosion-related issues but also susceptibility to detrimental effects of current flow can be increased or decreased. It is therefore important to define thresholds for the negative or possibly positive influence of electrical current flow on concrete/reinforced concrete microstructure.

2. Technical background

So far, 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 reinforce have been both reported (Wang et al. 2011, Chen et al. 2012). In a few extreme cases, severe structural damage was observed and recorded as a result of stray current leakage (Chen et al. 2012, Ding et al. 2008, Lingvay et al. 2011, Bertolini et al. 2004, Sheir et al. 1994, Jones 1978, Hamlin 1986). The influence of several accompanying factors such as: cement type, AC or DC current, current density, interruptions in the current circulation, as well as coexisting chlorides were also reported (Chen et al. 2012, Ding et al. 2008, Lingvay et al. 2011, Geng et al. 2008). AC currents are far less detrimental than DC currents, even at high current densities of 50 A/m². In contrast, DC would dramatically decrease bond strength within a few months at current density levels between 1 and 10 A/m² (Bertolini et al. 2007, Duranceau et al. 2011, Velivaskas et al. 1998, Chang 2003, Marcotte et al. 1999). The presence of even small amounts of chlorides e.g. 0.2 to 2 wt.%, leads to a remarkable decrease in the charge required for corrosion initiation (Bertolini et al. 2007). Numerical simulation for the influence of stray current and modelling the performance of reinforced concrete structures with this regard are reported (Yu-qiao et al. 2010, Peelen, Smulders, Steyn et al., Liu et al. 2011, Kerimov et al. 2006, Kim et al. 1999, Brichau et al. 1996, Weyers et al. 1998, Liang et al. 1999, 2002, Andrade 2010).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 (Bertolini et al. 2007, Kish 1981, Whiting 2003, Brown 1980 and references therein). Even, the hydrolytic degradation of cement-based materials via the application of voltage/current regimes in the range of 25 V and current densities not exceeding 1 A/m² has long been recognized (Wittmann 1997, Saito et al. 1992). 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 and most of the reported studies are with respect to corrosion issues only.

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 deeper investigation is needed in order to properly predict the behaviour of reinforced concrete in the above discussed environments. Within previous studies, related to impressed current CP for reinforced concrete, as well as DC current regimes as only simulation of CP (Koleva et al. 2008a, b, c), it was found out that current densities in the range of 5-30 mA/m² result in microstructural alterations of the bulk mortar and concrete matrix. The outcomes depend on the hydration stage and environmental conditions. These studies were mainly related to corrosion and CP. Therefore a systematic investigation on the influence of current flow on cement-based microstructure and definition of current limits, exposure conditions and time scales was not previously performed and is still lacking in the reported literature.

This work aims to bring clarity with respect to the above considerations and is an initial study in the frame of research on modelling and experimental validation of the effect of stray currents on cement-based systems. The emphasis is on mechanical and electrical properties and microstructural characteristics of plain mortar, subjected to DC stray current flow. The DC current regime of 10 mA/m² was chosen as a start-point investigation (current ranges of 100 mA/m², 1 A/m² and more than 10 A/m² are on-going). To avoid polarization/steel corrosion effects and with the aim to present an initial outlook on the influence of stray currents on bulk matrix properties, this work is related to non-reinforced specimens. Numerical simulation of the stray current distribution was performed and coupled to the bulk matrix properties. These outcomes will further serve as a basis for predicting stray current density distribution and resulting electrical and microstructural properties of cement-based systems.
3. Experimental materials and methods

3.1 Materials
Mortar cubes of 40 mm×40 mm×40 mm (Fig. 1) were cast from OPC CEM I42.5N, water-to-cement ratio of 0.5 and cement-to-sand ratio of 1:3. The chemical composition (in wt. %) of CEM I42.5N (ENCI, NL) is as follows: 63.9% CaO; 20.6% SiO₂; 5.01% Al₂O₃; 3.25% Fe₂O₃; 2.68% SO₃; 0.65% K₂O; 0.3% Na₂O.

Two groups of specimens were monitored: group R – reference/control group (no current flow involved) and group S – “stray current” group (mortar cubes subjected to stray current flow). Both groups were tested from 1 day until 84 days in two replicate series of tests. The mortar cubes from groups R and S 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 of 98% RH, 20°C for 24 hours; after de-moulding they were positioned in the relevant containers, Fig. 1, without – group R and with – group S current flowing in the medium.

3.2 Current regime
A simulation of stray current was achieved by injecting a DC current at the level of 10 mA/m², Fig. 1. The relevant surface area was calculated based on the geometry of the set-up, essentially the cross section A, Fig. 2a), of the environmental medium. This allows further estimation of cumulative current, flown through the mortar cubes, as stray current in the medium. A negative and a positive terminal were connected to a 25V source, the current level was adjusted via resistors in the circuit, Fig. 1, i.e. the cubes in the container are positioned in aqueous environment, where controlled stray DC flows throughout the experiment for 84 days.

3.3 Methods
3.3.1 Standard compressive strength
Tests were performed at the hydration ages of 24h, 3, 7, 14, 28, 56 and 84 days. The compressive strength tests (using CE04MATEST Srl, Italy) were performed on air-dry specimens - at each relevant hydration stage three replicates of each group were taken out from the conditioning set-up, cloth-dried and tested within a 30 min time interval. Before the test, a loading speed of 1.5 MPa/s and maximum load of 300 kN were set. The maximum applied load on the specimen was recorded and the compressive strength was calculated by dividing the maximum load at failure by cross-sectional area, in this case 1600 mm².

![Fig. 1](image1.png) (a) Experimental set-up for group S; (b) electrical circuit, where R1=120 kΩ and R2=20 kΩ are current adjusting resistances.

![Fig. 2](image2.png) (a) Schematic presentation, including geometry of the container, where h=4 cm, h1=2 cm, A=27x2 cm; (b) schematic of the electrical resistance measurement where 1 represents titanium plates (mesh) and 2 - mortar cubes.
3.3.2 Mortar electrical resistivity and water conductivity

Mortar electrical resistance was recorded via an AC “2-pin method”, Fig. 2b), where the “pins” are essentially metal plates with dimensions equal to the sides of the mortar cubes. For this measurement, a specially designed device, referred to as R-meter was used. By applying an alternating current of 1mA at a frequency of 1kHz, the R-meter outputs a DC voltage, which represents the actual resistance. Conversion to electrical resistivity is then possible through derivation from Ohm’s Law: \(\rho = \frac{R \cdot A}{l}\), where \(\rho\) is the resistivity in Ohm\(\cdot\)m, \(R\) is the resistance in Ohm, \(A\) is the cross-section of the mortar cube in \(m^2\), and \(l\) is the length in m. The resistance measurements were performed after current interruption of approx. 30 min but in immersed condition (i.e. wet mortar). Conductivity measurements for the testing environment were performed using a 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).

3.3.3 Microstructural analysis

Microstructural analysis was performed at the hydration ages of 24h, 7days and 28 days. The sample preparation followed well defined and accepted procedures of sample cutting, vacuum impregnation, grinding, polishing etc. which were after ceasing hydration in liquid nitrogen and freeze-drying of the samples to constant weight before impregnation (Ye et al. 2002, Ye 2003). 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 was 226 µm in length and 154 µm in width, with a resolution of 0.317 µm/pixel (corresponding to a magnification of 500×); the pore size considered for image analysis is larger than 0.317 µm. In order to quantify the pore structure, the 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 (Ye et al. 2002, Ye 2003, Hu et al. 2003, Hu 2004, Hu et al. 2005, Hu 2006 et al., Sumanasooriya et al. 2009, Serra 1982).

3.3.4 Mercury intrusion porosimetry (MIP)

Sample preparation for MIP analysis followed the aforementioned generally accepted procedure (Ye et al. 2002, Ye 2003, Hu et al. 2003, Sumanasooriya et al. 2009). The MIP tests for porosity and pore size distribution of the specimens were conducted in duplicate, using Micrometritics PoreSizer 9320 (with a max. pressure of 207 MPa). The Washburn equation (Washburn 1921) was used to calculate the pore diameter, intruded at each pressure step, which is shown as: \(D = \frac{4 \gamma \cos \theta}{P}\), where \(D\) is the pore diameter, \(\gamma\) is the surface tension of mercury, \(\theta\) is the contact angle between mercury and the pore wall and \(P\) is the applied pressure. The surface tension of mercury was 484 \(\times 10^3\) N/m and the contact angle was 130°. The measurement was conducted 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 (Washburn 1921), the pore size range detected is from 350 µm to 7 nm.

3.3.5 Chemical analysis

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 28-56 days were determined by plasma spectrometry using Inductive Coupled Plasma spectrometer (ICP-AES). The hydrated (chemically bound) water at certain hydrations age was determined according NEN 5931 (which is a standard loss of ignition test).

3.3.6 Numerical simulation

Numerical simulation of stray current was performed to obtain potential and current density distribution in the mortar cubes. The current density depends on the electrical resistivity/conductivity of the mortar and the external aqueous medium. The model used as input parameters electrical potential, electrical conductivity and relative permittivity for both mortar and water. The electrical potential difference between the positive and negative terminals is a direct measurement, using multi-meter. The water and mortar conductivity are also experimentally derived (section 3.3.2 above). The input for mortar and water relative permittivity of 4.5 and 80 F/m respectively were taken as literature data [Halabe et al. 1988, Bourdi et al. 2008, 2012]. The governing equations for the stray current model are as follows:

\[ \nabla \cdot J = \rho / \varepsilon \]  \hspace{1cm} (1)

\[ J = \sigma E \]  \hspace{1cm} (2)

\[ E = -\nabla \cdot V \]  \hspace{1cm} (3)

\[ \mathbf{B} = \mathbf{\varepsilon} \cdot \mathbf{E} \]  \hspace{1cm} (4)

where equation (1) gives the relationship between current density \(J\) (A/m²) and charge density \(\rho\) (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 (\(\nabla \cdot J = 0\)); 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 \(\sigma\) 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 \(\mathbf{B}\) (C/m²) and electric...
field \( \vec{E} \) (V/m) that describe the interaction between charged material with relative permittivity \( \varepsilon_r \) and vacuum permittivity \( \varepsilon_0 \). \( \vec{D} \) is related to the charge densities associated with this interaction, while \( \vec{E} \) is related to the forces and potential differences.

To solve the equations (1-4), initial and boundary condition need to be specified (see Fig. 3), as follows:

\[
\nabla \cdot \vec{J} = 0, \quad (x,y,z) \in A_o
\]

\[
V(x,y,z) = 0, \quad (x,y,z) \in A_n
\]

\[
V(x,y,z) = V, \quad (x,y,z) \in A_s
\]

\[
-n \cdot \vec{J} = 0, \quad (x,y,z) \in A_1, A_2, A_3
\]

where, \( A_o \) indicates the representative 3D volume model system i.e. \( A_1 \) and \( A_2 \) are the surface areas at the positive and negative terminals; \( A_1 \) (front surface part), \( A_2 \) (back surface part), and \( A_3 \) (bottom surface part) represent the surfaces without current flow due to electric insulation condition in the set-up (a wooden bottom plate). By surface area, the relevant cross sections of the aqueous environment are meant. These equations were implemented in the finite element method (FEM) of COMSOL Multiphysics V 4.2 software in the AC/DC module (Pryor 2011). The number (degree) of freedom, the maximum step-size and the number of iterations used in this model are 114011, 12, and 25 respectively.

4. Results

4.1 Chemical analysis – hydrated (chemically bound) 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 bound, interlayer, absorbed, free (capillary) water) (Basheer 2001). Chemically bound (hydrated) water is part of the hydration products, and could be released only with decomposition of hydrates. The bound 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 obtained wet chemically and the recorded values served as an indication of possibly different hydration mechanisms when stray current flow was involved (as in group S) compared to control conditions (group R). Figure 4 presents the amount of hydrated water (in percent per dry cement weight) for both groups R and S in the time interval of 1d – 84 days. The derived values can be considered as almost equal for both groups (just 1 to 2 wt.% difference). Apparently, within the time scale of this experiment pronounced alterations in hydrated water content due to current flow cannot be claimed. However, the observed differences are well in line with the recorded electrical resistivity for both R and S specimens (presented further below in Section 5) as well as the recorded compressive strength and microstructural characteristics (Sections 4.2 and 4.3).

4.2 Compressive strength.

Compressive strength, as an engineering property of cement-based materials reflecting mechanical performance, is generally expected to increase with cement hydration (i.e. with time and if no other external factors are present). Figure 5 presents the development of compressive strength for both control (R) and “stray current” (S) groups from initial conditioning (24h) until the end of the test (84 days). Three replicates per condition were tested. Considering the high level of structural heterogeneity of cement-based materials (and therefore the well known outcome of similar but never the same strength values even within a single batch of specimens), it can be stated that the average difference in strength is minimal (or practically none) between groups R and S. However, it can also be observed that after the initially stable increase of strength for specimens group S, similar to specimens group R, the former group shows an evident trend to maintain lower strength values (from 28 days and onwards). The recorded values are in line with the
percentage of bound water (Fig. 4) and are supported by microstructural observation of the bulk matrix.

4.3 Microstructural properties
The development of the pore structure in hardening cementitious materials is fundamental to their mechanical behaviour. It influences ion and water transport and their interaction as well as the diffusion characteristics of the bulk matrix. Previous studies on the influence of electrical current within CP applications revealed that a current flow in the range of 5 to 20 mA/m² brings about initial densification of the concrete bulk matrix, but leads later-on (more than 120 days of age) to enlargement of the interfacial transition zones and coarsening of the pore structure (Koleva et al. 2008a, b, c). Although the electrical current flow involved within this investigation is a simulation of stray current i.e. the relevant positive and negative terminals were not embedded in the mortar cubes but external, and therefore a direct comparison to previous results can not be made, similar influence on the material structure (including pore structure) of the hereby studied mortar specimens was expected.

Figure 6 depicts the calculated porosity and pore size distribution for the control specimens R and the “stray current” specimens S at the stages of 24h, 7d and 28 days. It should be noted that Fig. 6 presents porosity and pore size distribution values, which are calculated via image analysis (as previously introduced). The employed method can distinguish pore sizes larger than 0.317 µm. The derived values are not claimed to be absolute, but rather serve as a comparison of bulk matrix characteristics of equally handled samples from both groups R and S (via equal sample preparation respectively). Both S and R specimens present equal characteristics for the first time interval (24h). Development of the pore structure follows with cement hydration, resulting in densification of the matrix for both R and S groups. Porosity decreases from ~18% at 24h to ~14% for specimens R and ~10% for specimens S at 7 days age. The microstructure of specimens S is affected by enhanced ion and water transport in the matrix, resulting from parallel diffusion and migration controlled mechanisms in the presence of
electrical current flow, whereas diffusion controlled mechanisms only are relevant for group R.

The lower porosity values for group S at this stage are in line with the slightly higher amounts of hydrated water (Fig. 4) and would generally result in higher compressive strength (Fig. 5, strength development from 7 to 14 days). At the stage of 28 days, a reversed trend was observed for specimens S – porosity increases from ~10% to ~12%, whereas decreases only for specimens R (from 14.2% to 9.3%). The result supports the lower compressive strength values for specimens S, compared to specimens R at this stage (Fig. 5, 28 days and later stages).

Porosity and pore size distribution were also derived via conventional MIP tests, Fig. 7. Here again, absolute values are not claimed, neither a direct absolute comparison with pore structure parameters derived from image analysis can be made. For the hydration age of 28 days, the MIP results present analogical trend of material behaviour as previously defined within image analysis for this time interval (Fig. 7a, b); the rectangular area in Fig. 7a defines the region, where image analysis can determine porosity and pore size). Coarser pore structure for specimens S was derived at 28 days, relevant to pores larger than 10 μm and the gel pore family (below 0.1 μm) – Fig. 7b; total and effective porosity for specimens S are also slightly higher, compared to specimens R (Fig. 7a).

At 84 days of age, the total and effective porosity for both S and R groups decrease (Fig. 7c), compared to 28 days of age (Fig. 7a). For specimens S, the trend of higher than specimens R (total and effective porosity) was maintained (Fig. 7c) and a more pronounced difference in pore distribution density was observed i.e. capillary porosity increased as evident from the well pronounced peak between 1 μm and 0.1 μm in the differential curve for specimen S – Fig. 7d. The results form microstructural analysis (both image analysis, Fig. 6 and MIP analysis, Fig. 7 are “visualized” by Fig. 8, presenting ESEM micrographs of the bulk mortar matrix (at equal magnification of 500x) for the control specimens R (left column) and the “stray current” specimens S (right column).

Well visible is the denser matrix in specimens S at 7 days of age (Fig. 8 top); followed by coarsening (compared to R) at 28 days of age (Fig. 8 middle) and an even coarser pore structure for specimens S at 84 days of age (Fig. 8 bottom).

The global performance of the here investigated mortar specimens is determined by the above discussed microstructural characteristics. The derived pore structure parameters support the findings for development of compressive strength and are also in line with the electrical properties (electrical resistivity in this case) of the investigated specimens. Discussion on the experimental results and additional supporting evidence for the different material development in conditions of current flow (as within specimens group S) will be presented in what follows.

5. Discussion

The electrical resistivity, conductivity respectively, is a 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 continuously performed throughout the total duration of the test. Figure 9 depicts derived electrical resistivity values for both groups S and R: from initial values (24h) until 84 days. The plots in Fig. 9 additionally depict information for the stray current density that flows through each cube (for the S specimens), and the hypothetic current density for the control group R, calculated with numerical simulation (Section 6 further below). As can be observed, electrical resistivity increases with time for both S and 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, Fig. 9b). At the latest time interval (84 days, Fig. 9f) the 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, which actually corresponds well to the lower resistivity values for group S. However, no straightforward relation can be made, since microstructural alterations play an important role as well; the average stray current density, flowing per cube decreases with time which is with increasing the electrical resistivity of the matrix, and maintains higher values for the S specimens. This corresponds to the lower electrical resistivity, lower compressive strength and the coarser pore structure in specimens S.

After correlating the results from chemical analysis (hydrated (bound) water content), compressive strength tests, microstructural analysis of the bulk mortar matrix and electrical properties, it can be stated that the stray DC current, flowing through the specimens group S, exerts changes in material behaviour. Compared to group R,
initially similar or higher values of hydrated water content were recorded for group S at earlier stages, whereas still increasing, but slightly lower values compared to the control group R were recorded later on (Fig. 4). 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 initially accelerates cement hydration for group S. This is confirmed by increasing compressive strength values for group S (Fig. 5), initially denser pore structure e.g. 7 days age, Figs. 6-8) and higher electrical resistivity of the mortar specimens S, compared to specimens R – Fig. 9b). The effect shows a reversed trend on later stages (after 28 days of age), which is denoted to the simultaneous contribution of stray current flow and concentration gradients on cement hydration, as well as possible calcium and alkali ions leaching. These latter phenomena, denoted to the influence of current/voltage flow in water environment have already long been recognized and reported to result in hydrolytic degradation of hardened cement-based materials within less than 50 days of conditioning in similar to the hereby discussed environment (Saito et al., 1992, Wittmann 1997). Consequently, alterations in microstructural and electrical properties, further resulting in lower electrical resistivity (Fig. 9d-f), lower compressive strength (Fig. 5) and coarser pore structure (Figs. 6-8) were expected and are actually as recorded starting 28 days of age for specimens S, compared to the control cases (specimens R). These trends

Fig. 9 Comparison of electrical resistivity values (columns) in Ohm•m for mortar specimens S and R (both in immersed condition and identical water levels) at hydration ages of 24h (a), 3 days (b), 7 days (c) 28 days (d) 56 days (e) and 84 days (f). The number of cubes (depicted values respectively) reduces with time, relevant to removing of 4 replicates per stage for the relevant tests (the plots contain current density values as cumulative stray current flow per cube as calculated by numerical simulation, discussed further below in Section 6).
and dependencies, although relatively less pronounced within the hereby relevant period of 84 days, are expected to be significantly more evident for longer conditioning, which is subject to an on-going investigation.

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. 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, leaching cannot be claimed in the generally accepted sense of these types of experiments, since the mortar cubes were immersed in stagnant water that was not exchanged during the tests, but only maintained at the same level by adding fresh water. However, the recorded calcium, sodium and potassium concentrations at the beginning of the test and after 28 to 56 days show five to ten or more times increased ion concentrations within conditioning (Table 1).

For this experiment, leaching will result from concentration and pH gradients between the cement-matrix and the external (tap water) environment (the pH values were measured to be approx. 8 at the beginning of the test and approx. 13 after 28 days). Leaching is expected to be accelerated in the presence of current flow. Although conductivity values of the environment for S and R groups and ion concentration are not far different, conductivity, as well as K⁺ and Na⁺ concentrations) for the S groups were lower, whereas Ca²⁺ concentration was slightly higher, compared to the conditioning water for group R (no absolute values are claimed, but a comparison of initial and cumulative 28 to 56 days values are given). Since alkali ion concentrations also increase in the conditioning water for group R, the most plausible reason for the coarsening of the pore structure in specimens S is the electrical current contribution towards enhanced ion and water migration. It can therefore be concluded that the electrical current flow 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.

6. Numerical simulation and correlation of results

Considering all experimental data and the above-discussed outcomes of this investigation, a further objective of this study was to initiate and present first trials on numerical simulation of the dependence of stray current density, flown per cube and the relevant development of mechanical and microstructural properties. Figure 10 presents an example for the numerical simulation of potential (Fig. 10a) and current (Fig. 10b, c) distribution in the specimens S. The simulation can provide data for the distribution of current density flow per cube i.e. current distribution lines within the matrix of each cube (Fig. 10b) or per defined cross section of each cube (Fig. 10c, top and bottom sections are depicted). This is of particular interest when aiming to correlate bulk matrix properties as strength or resistivity – in this case the total cumulative stray current, flown per cube (Fig. 10b) can be coupled to the obtained results; or similarly – for the case of porosity and pore size analysis via image analysis – the current flow through a relevant (in our case middle section) of each cube (Fig. 10c) can be correlated to derived pore structure parameters in this same section. These correlations, however, need to consider also if the cubes were near the negative or near the positive terminals of the conditioning set-up, since the relevant opposite ion flow determines structural characteristics (Wittmann 1997, Koleva et al. 2008). For this experiment the above correlation were not performed and will be subject to a future work.

At the beginning of the test (1 day, Fig. 11a, b), the level of current density, flowing in the immersed (bottom) sections of the cubes (Fig. 11b) almost equals the current distribution flow in the external aqueous environment, whereas lower currents are relevant for the top (higher resistant) sections of the cubes (Fig. 11a). After 7 days of conditioning (and with time of cement hydration) densification of the matrix and developing of mechanical strength lead to lower current, flowing through the highly resistive top sections of the cubes (Fig. 11c). The bottom sections also become more resistive (Fig. 11d). At later stages (28 and 84 days, Fig. 11e-h), the current flow decreases through 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 stray current is supplied, is constant. The difference in the actual current density, flowing through each 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 that flows through each cube is different and this is well visible from Fig. 11. For example

<table>
<thead>
<tr>
<th>Conditioning water group</th>
<th>pH</th>
<th>Na⁺, g/l</th>
<th>K⁺, g/l</th>
<th>Ca²⁺, g/l</th>
<th>σ, S/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>8.5</td>
<td>0.041</td>
<td>0.009</td>
<td>0.048</td>
<td>0.92</td>
</tr>
<tr>
<td>S</td>
<td>13.1</td>
<td>0.032</td>
<td>0.563</td>
<td>0.391</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 1 pH, alkali ions concentration and conductivity of water environment.
at 7 days of age (Fig. 11d) the bottom sections of the cubes in the upper and middle part of the experimental set-up (indicated with arrows in Fig. 11d) “receive” higher current, compared to those in the bottom part (i.e. their electrical resistivity is lower). At 28 days some cubes are more resistant to current flow (arrows in Fig. 11f), compared to others. Gradually (e.g. 84 days, Fig. 11g, f), the cubes becomes more and more resistive to current flow (also reflected by gradual increase in electrical resistivity values, Fig. 9, which however maintain lower, compared to the control R group). A simulation for the “hypothetic current flow” can be performed for the cubes group R (control case) - the resulting current flow distribution for 28 days for example is as presented in Fig. 13. Well seen is that for equal environmental conditions, as well as equal current levels applied, the
current density, flowing through specimens R will be significantly lower compared to that in specimens S (compare Fig. 11e, f with Fig. 13) in both top (Fig. 13 left) and bottom (Fig. 13 right) sections of the cubes.

The model can thus provide the distribution of current flow per cube and the current distribution flow with time of conditioning. With additional input parameters (as matrix permeability for example) and mathematical transformations (which are subject to on-going study) the level of current flow can be correlated to microstructural and mechanical properties for each cube. The end result would be a correlation of stray current flow 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 and for various current regimes.
7. Conclusions

The paper discussed microstructural, mechanical and electrical properties of mortar specimens in conditions simulating stray current flow, compared to control, “no-current” conditions. Numerical simulation for the distribution of the stray current flow in aqueous medium and the presence of mortar cubes was performed and validated with experimentally derived results. The following conclusions can be summarized:

- At the level of 10 mA/m² (surface area of the cross section of the conditioning environment in direction of current flow) the stray current flow results in slightly higher percentages of hydrated water content and denser bulk matrix of the mortar bulk matrix, which is due to reduced porosity and critical pore size;
- Compressive strength and electrical resistivity for the mortar, maintained in conditions of stray current flow (group S) increased with time, but maintained lower values, compared to these for the control group R;
- At later conditioning intervals (28 to 84 days of age), the stray current flow brings about microstructural alterations in terms of coarsening of the mortar bulk matrix, with a possible contribution of 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 accelerated ion and water migration in the presence of current flow.
- Apart from diffusion, ion and water migration have a positive effect on cement-based properties; however, the enhanced water and ion transport on later stages induce 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 e.g. sat. Ca(OH)₂, fully immersed or sealed conditions, in order to separately evaluate leaching and/or stray current-induced effects. The ongoing studies with different current regimes will potentially allow defining thresholds for negative (or initially positive) effects of current flow on cement-based microstructure.

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References


IEC 61439 (Italian standard), Part 1 and Part 2, “Low voltage assemblies and relevant applicability.”


