THE EFFECT OF ELECTRICAL STRAY CURRENT ON MATERIAL PROPERTIES OF MORTAR SPECIMENS

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ABSTRACT

Well known is that stray electrical current i.e. current with a spatial distribution in any conductive environment, can affect civil structures, e.g. initiate or enhance steel corrosion or affect microstructural and mechanical properties of the cement-based bulk matrix. While the former is related to polarization effects in conditions of current flow, the latter is generally a consequence of leaching phenomena, which normally occurs due to concentration gradients. In the case of current flow, concentration gradients’ controlled diffusion is accompanied by migration i.e. ion and water transport in an electrical field. Although these conditions are not specifically and intentionally arranged, with regard to civil structures they would be inevitable for the underground or water submerged sections. Related to a study on the effect of stray currents on cement-based materials microstructure, leaching processes were observed, accompanied by alterations in pore network parameters (as porosity and pore size distribution) and mechanical properties (as compressive strength). Two current regimes were investigated i.e. 100mA/m² and 1A/m² as applied current densities and outcomes compared to properties of the investigated specimens in “natural leaching” conditions or control, no-current cases. The investigation shows indeed enhanced alterations of material properties for the “under current” conditions, substantiated by chemical analysis, mercury intrusion porosimetry and mechanical tests.

INTRODUCTION

Concrete is a solid, porous material. When exposed to moisture during service life, deterioration or degradation of the bulk matrix can result from calcium leaching into the external environment. Deterioration of concrete due to leaching occurs progressively when a structure is in contact with water for a long time such as underground storage, dams, water tanks and radioactive waste disposal containers (Jain & Neithalath (2009); Puertas et al. (2010); Marinoni et al. (2008); Gaitero et al. (2008); An Cheng et al. (2012)). The leaching process results from concentration gradients between the pore solution of the cement-based material and the external environment, surrounding the structure. These gradients accelerate the diffusion process of all species present in the pore solution of the cement-based material towards the external environment – basically, ion and water migration is at hand – which disturbs the local equilibrium between the solid and the liquid phases. Consequently, a partial dissolution of the cement based matrix occurs in order to restore the initial equilibrium (Marc et al. (2000); Nguyen et al. (2007)). The leaching process generally begins with a total dissolution of portlandite (C-H), then ettringite, followed by a progressive decalcification of the C-S-H phase. Leaching will progress even further, following the square root of time (\( \sqrt{t} \) ) law (Ulm et al. (1999)).

Several studies report in more detail on the chemical degradation of cement-based materials with respect to leaching (Carde et al. (1996); Le Bell’ego et al (2001); Ulm et al (2003)). Although a relatively slow process in natural environment (unless specific conditions apply, e.g. externally low pH, SO₄-containing medium, etc.), calcium leaching would increase porosity, permeability and diffusivity of the concrete bulk matrix, resulting in higher risks for aggressive agents (e.g. chloride ions) penetration and consequently reduced concrete structures durability in the long term (Cheng et al. (2012); Roziere et al. (2009); Larrard et al (2010); Jacques et al. (2010), Nguyen et al. (2007); Carde et al. (1996); Le Bell’ego et al. (2001), Ulm et al. (1999); Heukamp et al (2001); Ulm et al. (1999)). Therefore, studies on the leaching behaviour and related consequences in cement-based materials are performed, using various simulation and acceleration techniques, e.g.: temperature (An Cheng et al. (2012), Larrard et al. (2010)), electrical field (Saito et al. (1992)), deionised water or replacement of the latter, using different agent (e.g. ammonium...
nitrate), all these applied so as to increase concentration gradients between the interstitial solution and the external environment. Although many studies have investigated the leaching phenomena in cement-based systems, the effect of electrical field as such and moreover, the influence of stray current on the accelerated leaching process is not largely reported (Atkinson et al. (1987); Atkinson & Guppy (1987), Berner (1998); Saito & Nakane (1999); Saito & Deguchi (2000). When current is applied, ions in a solution move towards the opposite electrodes under a direct-current potential gradient. Ions in the solid matrix of a cement-based material similarly move to the opposite poles, e.g. cations (Na+, K+, Ca2+) move towards the cathode, anions (e.g. Cl−, OH-) move toward the anode (Saito & Deguchi (2000); Brown & Clifton (1988)). However, ion and water transport (both diffusion and migration) in cement based materials is occurring in the pore water and this transport will be defined by the nature and characteristics of the pore structure (interconnectivity, permeability, tortuosity, etc.).

This work reports on the effect of stray current on material properties of mortar specimens, submerged in water environment. Although studying the leaching effects was not the main purpose of these tests, but rather the effect of current flow on microstructural and mechanical properties were of main interest, accelerated leaching was observed as a result of the involved current flow. Experimental results on porosity, permeability, compressive strength and chemical analysis of the external environment from 24h after casting until 112 days of cement hydration are presented and discussed. The results are a comparison of two current regimes and a control (no-current involving) condition.

**EXPERIMENTAL MATERIALS AND METHODS**

**Materials**

The studied specimens were mortar cubes of 40 mm x 40 mm x 40 mm, 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.

**Current Regime**

Figure 1 shows a schematic presentation of the experimental set up for stray current regime using current density of 100 mA/m² and 1 A/m². The experimental set up is as previously used and reported (Susanto et al. (2013)). The current density was adjusted by additional resistors (R₁=2700 ohm and R₂=270 ohm) in the electrical circuit. The mortar cubes were completely submerged, tap water was used as external medium. The stray current simulation was applied from 24h hydration age (immediately after de-moulding of the specimens) and until 112 days of age.

Fig. 1: (a) Experimental set-up for group S (b) Equivalent of electrical circuit for experimental set up, where R₁=2700 Ω and R₂=270 Ω are current adjusting resistances

**Methods**

**Standard Compressive Strength**

Standard compressive strength tests were performed on 40×40×40 mm mortar cubes at the hydration ages of 3, 14, 28, and 112 days. Three replicate specimens were tested per hydration age.
Mercury Intrusion Porosimetry (MIP)
The sample preparation for MIP tests followed generally accepted procedures (Sumanasooriya et al. (2009); Hu (2004)). 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.

RESULTS AND DISCUSSION

Compressive Strength
Figure 2 presents the evolution of compressive strength for both control (R) and stray current (S) regime from initial conditioning until 112 days (group S presents two subgroups, for which current density of 100mA/m\(^2\) and 1 A/m\(^2\) are relevant). As seen from the plot, only a minor influence of the current flow was observed at early hydration ages (3 and 14 days). Generally, compressive strength increases with time and with cement hydration. While this trend is as expected for the control specimens, increasing trends but lower values were recorded for the S groups with pronounced difference for the case when higher current densities were involved. Group S at 1mA/m\(^2\) presents the lowest compressive strength after 112 days of cement hydration – Fig.2. The results indicate that the higher current density apparently alters the microstructural properties as a result of which mechanical performance is reduced.

![Compressive strength measurements](image)

Fig. 2: Compressive strength versus hydration age for control specimens and specimens under stray current (specimens were maintained in submerged conditions)

Chemical Analysis of The Environmental Medium
Figure 3 depicts the concentration of leached calcium, sodium and potassium in mg/l of the environmental medium (tap water), recorded at certain hydration stage. At each hydration age of interest, the water solution was exchanged with a new one in order to better evaluate the cumulative ion concentrations. After initially rapid increase in ion concentration in the external water environment, the trend is towards a less pronounced leaching, which is as expected due to the already hardened cement-based matrix. A relatively stable increase in cumulative alkali concentrations (calcium, potassium and sodium) is observed at the end of the testing period. As seen from Fig.3a, the largest effect of stray current is on the leaching of calcium, whereas potassium and sodium leaching are somewhat similar as trend to the control cases – sodium basically is recorded to be the same for each condition. In other words, the leaching effects due to stray current flow are in terms calcium, as actually reported in other studies (Saito et al. (1992)).

As aforesaid, the consequence of leaching phenomena is an increase in the material porosity and a global decrease in mechanical performance (strength) (Cheng et al. (2012); Roziere et al. (2009); Larrard et al. (2010); Jacques et al. (2010); Nguyen et al. (2007); Carde et al. (1996); Le Bell’ego et al. (2001); Ulm et al. (1999); Heukamp et al. (2001); Rosa et al. (1913); Guirguis (1987); Weyers et al.)
Calcium leaching (Fig. 3a) and altered material structure, reflected in reduced compressive strength (Fig. 2) are supporting evidence for the commented behaviour.

Fig. 3: Evolution of cumulative leached calcium (a), potassium (b), and sodium (c) until 44 days (renewed fresh water at 4d and 15d)

Microstructural Properties

The pore structure is a decisive physical parameter that controls permeability of concrete/mortar. Mercury intrusion porosimetry (MIP) is one of the powerful tools for qualitative analysis of the pore structure of cement-based systems. Mercury intrusion is frequently used for the characterization of porous materials, giving assess to microstructural parameters such as porosity and pore size distribution.

In this study, pore structure analysis via MIP was performed for both control and stray current conditions. Figures 4 and 5 depict porosity and differential pore size distribution for 3, 14, 28 and 112 days. At early stage (3d) both S and R specimens present similar porosity. Initial coarsening of the matrix for S specimens is recorded at 14 days. At 28 and 112 days, the difference is more pronounced and apparently related to the prolonged leaching of alkali ions, in addition to enhanced ion and water migration in the conditions of electrical current flow. The influences of stray current are obvious both of 100 mA/m$^2$ and 1 A/m$^2$. The higher the current density flow, the higher the porosity increase. Figure 4 also shows that the differential pore volume plot i.e. $dV/d(\log D)$ versus pore diameter on log scale, used to estimate the pore volume contribution arising from individual diameters. The mortar specimens with current density 1 A/m$^2$ presents higher differential pore volume for the finer pores at 3d and 14d. An opposite trend can be seen at 28 and 112 days i.e. coarser pores dominated in S specimens. In general, the total porosity and
differential pore volume decrease with time of cement hydration. A different trend was observed in this study, where the differential pore volume curves show an increase in the pore size (capillary pores) and redistribution in the larger pore family with time of hydration. Figure 5 depicts a comparison of derived porosity values for the total duration of the test. Figure 6 presents permeability, calculated on the basis of equation $k' = d_c^2 \eta \varphi$, where $d_c$ is a length scale that characterizes the pore diameter that dominates fluid transport, $\eta$ is dimensionless parameter that takes into account the tortuosity and connectivity of the pore network and $\varphi$ is the porosity. All above parameters ($d_c$, $\eta$, and $\varphi$) can be derived from MIP measurements i.e. the threshold pore diameter ($d_c$), the total porosity ($\eta$), and the effective porosity ($\varphi$) (Ma et al. (2012); Garboczi et al. (1990)) can be experimentally derived and further correlated to approximate permeability. It can be observed that permeability naturally decreases with cement hydration. After the age of 14 days, however, values remain more or less constant with further hydration – higher values are recorded for the specimens under current flow.
CONCLUSIONS

This paper presents a study on the influence of stray current on material and mechanical properties of cement-based materials in submerged (water) conditions. The following conclusions have been drawn:

(1) Compressive strength for specimens subjected to electrical current flow, increases with time but maintains lower values, compared to these for control (no current) conditions. Obviously, the electrical current flow enhances water and ion transport, followed by enhanced alkali ions leaching and therefore reduced mechanical properties at the latest stages of cement hydration.

(2) At early stages (3d), there is no significant difference in the amounts of calcium, leached out of the system for both stray current and control specimens. However, after 14 days to 112 days the
difference is more pronounced especially for the specimens under current level of 1 A/m². There is no significance difference in the sodium and potassium leaching for all tested conditions.

3) Stray current induces increase in porosity and permeability of the cement-based system, which is for this experiment attributed to leaching effects. Additional effects of stray current on bulk matrix properties and interfacial transition zones are possible but not subject to this investigation.

REFERENCES


