The effect of water-to-cement ratio and curing on material properties of mortar specimens in stray current conditions

Agus Susanto, Dessi A. Koleva, Klaas van Breugel

Journal of Advanced Concrete Technology, volume 15 (2017), pp. 627-643

Related Papers Click to Download full PDF!

Mechanical, electrical and microstructural properties of cement-based materials in conditions of stray current flow

Agus Susanto, Dessi A. Koleva, U*~: @ Copuroglu, Kees van Beek, Klaas van Breugel

Journal of Advanced Concrete Technology, volume 11 (2013), pp. 119-134

Electric conductivity and chloride ingress in hardened cement paste

Kiyofumi Kurumisawa, Toyoharu Nawa

Journal of Advanced Concrete Technology, volume 14 (2016), pp. 87-94

Stray current-induced development of cement-based microstructure in water-submerged, Ca(OH)₂-submerged and sealed conditions

Agus Susanto, Dessi A. Koleva, Klaas van Breugel, Kees van Beek

Journal of Advanced Concrete Technology, volume 15 (2017), pp. 244-268

Click to Submit your Papers

Japan Concrete Institute - <http://www.j-act.org>

Scientific paper

The Effect of Water-to-Cement Ratio and Curing on Material Properties of Mortar Specimens in Stray Current Conditions

Agus Susanto^{1*}, Dessi A. Koleva² and Klaas van Breugel³

Received 20 January 2017, accepted 21 October 2017

doi:10.3151/jact.15.627

Abstract

This work reports on the synergetic effect of water-to-cement ratio, curing conditions, varying external environment and stray current on the microstructural (porosity and pore size), electrical (resistivity) and mechanical (compressive strength) properties of 28 days-cured cement-based materials. The influence of curing on porosity and pore size, in stray current conditions, was assessed by correlating the performance of 28 days cured mortar with that of fresh (24h-cured only) mortar specimens in identical environmental medium.

Three different levels of electrical current density (i.e. 10mA/m², 100 mA/m² and 1 A/m²) were applied to simulate stray current flow through hardened mortar specimens with water-to-cement ratio of 0.5 and 0.35. Different environmental conditions were employed i.e. sealed conditions, partly immersed, and fully submerged in water and calcium hydroxide medium. Microstructural, mechanical and electrical properties were monitored in the course of 140 days. The outcomes suggest a potentially positive effect of the stray current, where water and/or humidity exchange with the external environment is restricted. The potential for this positive effect was experimentally supported through the recorded matrix densification and increased compressive strength of mortar specimens, subjected to stray current and treated in calcium hydroxide and/or sealed conditions, compared to equally handled and treated control cases.

In contrast, for water submerged mortar specimens, subjected to stray current, coarsening of the bulk matrix and reduced compressive strength were observed. The outcomes were irrespective of w/c ratio and curing conditions. The effect of stray current was found to be predominantly determined by the current density level and increased at values > 100mA/m². This would result in compromised mechanical properties and potentially reduced performance of cement-based materials within service life. Therefore, concrete curing and conditioning on site need to include considerations for the potential effect of stray currents.

1. Introduction

From the view point of cement chemistry, hydration is the reaction of cement with water, resulting in setting and hardening of the hydrated cement paste. The term 'setting' means a rather sudden loss of plasticity of the original paste and its conversion to a solid material with a barely measurable strength. The term 'hardening' refers to the development of hardness and strength that follows the setting phase (Hewlett 2003). For a complete hydration, cement must be mixed with a sufficient amount of water, commonly represented by the water-to-cement ratio in a concrete mix design.

Concrete can be divided into fresh concrete and hardened concrete. Fresh concrete is the stage when setting

and hardening did not start yet. The properties of fresh and hardened concrete depend mainly on the curing conditions after casting and during cement hydration. Curing is a process of controlling the external temperature and moisture after casting and during concrete hydration. Proper curing plays an important role to obtain the designed strength and maximum concrete durability (Wang *et al.* 2002). In addition, improper curing results in undesired effects such as lower strength, cracking, low resistance to weathering, high permeability, dusting (Neville 1995; ACI 1981; ACI 1982; Samir *et al.* 1988). The influence of curing is significant at early ages and since strength development of concrete occurs most rapidly at early age, the greatest benefit from curing is achieved during this period (Troxell *et al.* 1968). The duration of adequate curing time depends on several factors such as mixture proportions, specified strength, size and shape of the concrete member, environmental and exposure conditions (IS 2000). In general, 28 days curing is required for cement-based materials, resulting in properties (both mechanical and microstructural), sufficiently developed for the required performance.

While measures can be taken for optimum curing on site, the hydration process, and concrete hardening respectively, can be affected by variety of external factors. Although some of these, as the above mentioned optimum humidity and air tightness, can be controlled, oth-

¹PhD Student, Faculty of Civil Engineering and Geosciences, Materials and Environment, Delft University of Technology, Delft, The Netherlands.

*Corresponding author, E-mail: a.susanto@tudelft.nl

²Assistant Professor, Delft University of Technology, Faculty of Civil Engineering and Geosciences, Materials and Environment, Delft, The Netherlands.

³Professor, Faculty of Civil Engineering and Geosciences, Materials and Environment, Delft University of Technology, Delft, The Netherlands.

ers are unpredictable and cannot be easily controlled. Such an effect of external environment, that is hard to control in practical applications, is stray current in the vicinity of a newly built structure (or freshly poured formwork mixtures on site). Stray current is a “leakage” of electrical current from metal conductors or electrical installations, where a non-proper or compromised grounding are at hand. Stray current can flow in any conductive environment (e.g. through soil) and can be “picked up” from near-by structures e.g. steel reinforcement in concrete.

Along with consequences for the steel reinforcement, as stray current-induced steel corrosion (Bertolini *et al.* 2007), a stray DC current flow can exert modification of the bulk matrix and lead to structural degradation (Susanto *et al.* 2013). Modification of the bulk matrix, in view of altered microstructural properties and steel/cement paste interface properties, were also studied in detail and reported to be induced by DC current flow within cathodic protection applications (Koleva *et al.* 2006, 2007, 2009, 2010). Cathodic protection normally applies DC current in a relatively low range of 5 to 20 mA/m². The level of stray current encountered in real practice was reported to be in a wide range: from 1 - 1.5 mA/m² (Charalambous *et al.* 2014; Aylott *et al.* 2013), to levels, higher than 1 - 1.5 A/m² (Galsgaard and Nielsen 2006). The exact level of stray current is hard to measure and/or predict. A major contributing factor is the resistivity of the medium, where stray current would flow. Of equal significance is the speed of stray current “discharge” or “dissipation” from a conductive path (e.g. steel reinforcement). Therefore, many environmental factors are to be considered before exact levels for stray current flow can be stated. More details on these aspects, along with a discussion on standards to minimize stray current effects, have been recently reported (Susanto *et al.* 2017).

One of the main consequences of stray current, especially for a fresh (not hardened, not sealed) cement-based material, is the effect on water and ion transport in the matrix. In an electrical field, ion and water migration will add-up to the internal diffusion-controlled mechanisms within cement hydration, resulting in altered hydration process. While migration can be positive at very early stages of the bulk matrix development, e.g. resulting in the so-called “electrical curing” (Bredenkamp *et al.* 1993), it can be also detrimental. The negative effect of stray current will be pronounced in conditions of direct contact of external environment and the concrete structure, when concentration gradient is present e.g. underground structures in contact with soil. The result will be enhanced alkali ions leaching-out and pore network coarsening, both during and after hardening of the still young concrete matrix, but also later on, within maturity development (Susanto *et al.* 2017). Therefore, concrete curing and conditioning on site need

to include considerations for the potential effect of stray currents. Additionally, the age of the cement-based material, at which stray currents affect and/or induce ion and water migration, subsequently change the on-going cement hydration, would potentially determine the level of these positive or negative effects.

In order to address the above considerations, the aim of this study was to investigate the influence of stray current on the properties of already hardened, initially cured for 28 days mortar specimens. Additionally, an objective was to also elucidate the effect of curing on the properties of a mortar matrix subjected to stray current (properties in hardened vs fresh state). Hence, a correlation is made to the pore network development in stray current conditions of a fresh, 24 hours-cured only, mortar in water-submerged, Ca(OH)₂-submerged and sealed conditions.

2. Materials and experimental methods

2.1 Materials

Mortar cubes of 40 mm×40 mm×40 mm were cast, using OPC CEM I 42.5N with w/c ratio of 0.5 and 0.35. The cement-to-sand ratio used was 1:3. The chemical composition (in wt. %) of CEM I 42.5N (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. After casting and prior to conditioning, the specimens were cured in a fog-room of 98% RH, at 20°C for 28 days.

2.2 Sample designation and current regimes

The 28-day cured mortar specimens were cast in two main groups, differing in w/c ratio i.e. 0.35 and 0.5. These two specimens' groups were presented by four sub-groups: 1) control group - no current involved; 2) group “10 mA/m²”; 3) group “100 mA/m²” and 4) group “1 A/m²”, where DC current was applied at the respective current levels. The samples designation (and relevant external medium) is given in the **Table 1**. The experiments were conducted in submerged, partly submerged and sealed conditions and varying environment (water, Ca(OH)₂ solution). Sample designation 28d are all specimen groups (**Table 1**) subject to this work, cured for 28 days and conditioned for 140 days. The notation “24h” in some specimens' designation refers to mortar of w/c ratio 0.5, cured for only 24 hours. Some discussion and results on “24h” specimens are presented together with outcomes for the w/c 0.5, 28 days cured mortar for comparative purposes only. This is in view of the objective of this work to report on the combined effect of curing and stray current on material properties. The 24h-cured specimens were identically prepared and conditioned, details on these are as reported in (Susanto *et al.* 2017).

Table 1 Sample designation and experimental conditions.

Specimens groups 1. 28d cured	Sample designation	Experimental conditions				
		Half immersed		Fully immersed		Sealed
		H ₂ O	Ca(OH) ₂	H ₂ O	Ca(OH) ₂	
Control	R1/2,H ₂ O, 28d (Control-1/2 H ₂ O,28d)	×				
	R1/2,H ₂ O, 28d (Control-1/2 CH,28d)		×			
	R full, H ₂ O, 28d			×		
	R full, CH, 28d				×	
	R sealed, 28d					×
10mA/m ²	10mA,H ₂ O, 28d (10mA/m ² -H ₂ O,28d)	×				
	10mA,CH, 28d (10mA/m ² -CH,28d)		×			
100mA/m ²	100mA,H ₂ O,28d (100mA/m ² -H ₂ O,28d)			×		
	100mA,CH, 28d (100mA/m ² -CH,28d)				×	
	100mA sealed, 28d					×
1A/m ²	1A,H ₂ O, 28d (1A/m ² -H ₂ O,28d)			×		
	1A,CH, 28d (1A/m ² -CH,28d)				×	
	1A sealed, 28d					×
2. 24h cured	Designation of 24h refers to the 24h cured specimens in identical to the above regimes					

The current regimes were applied through external (DC) current sources. The experimental set-up for the hereby reported 28 days cured specimens is presented in **Fig. 1**. For partly submerged and fully submerged conditions the specimens were positioned in water or Ca(OH)₂ solution and the current was applied via external, positioned in the aqueous medium, conductors (metal plates), following previously reported set-up (Susanto *et al.* 2013, 2017). For sealed condition (**Fig. 1**), electrical connections were made to apply electrical current through initially cast-in electrodes (brass mesh plates) on the two opposite sides of each cube. Specifically designed (sealed) mould allowed maintaining the specimens in the same position throughout the test. The electrodes also served the purpose of measuring electrical resistivity.

2.3 Experimental methods

2.3.1 Standard compressive strength

Standard compressive strength tests were performed on the 40 mm × 40 mm × 40 mm mortar cubes at the hydration age of 28 days as initial measurement and later on after 3, 7, 14, 56, 84 and 112 days of conditioning (i.e. 31, 42, 84, 112 and 140 days of age). Three repli-

cate mortar specimens were taken out from the conditioning set-up and tested within a 5 minutes time interval.

2.3.2 Mercury intrusion porosimetry (MIP)

MIP tests were performed to determine porosity and pore size distribution of the bulk matrix according to standard sample preparation and measurement procedures, as already reported in detail in previous works and in the relevant state-of-the-art (Washburn 1921; Susanto *et al.* 2013, 2017). The total porosity of mortar specimens can be calculated from the total volume of intruded mercury at the maximum experimental pressure, divided by the bulk volume of the mortar specimen (Ye 2003). The pore size distribution is defined as the pore volume per unit interval of pore diameter (Ritter and Drake 1945). For cement paste and mortar specimens, several peaks can be found in the pore size distribution differential curve obtained from MIP data. These peaks are the so-called critical pore diameters (Cook *et al.* 1999). According to Katz and Thompson (1986), the critical pore diameter can also be identified experimentally from the inflection point in the cumulative intrusion curve. In this study, the critical pore diameter is

Fig. 1 a) Experimental set-up for mortar specimens under electrical current flow with multiplexer and PC data recorder to record resistance; b) electrical circuit, where R_s is resistor to adjust electrical current flow through the mortar specimen.

determined from the peak, which corresponds to the lowest value of recorded pore diameter.

2.3.3 Mortar electrical resistivity

Various approaches for deriving electrical resistivity of cement-based materials are reported and in use, e.g. using impedance measurements (Kurumisawa and Nawa 2016) or similar to our work – deriving resistivity based on recorded resistance values (McCarter *et al.* 2001). The electrical resistivity of mortar in this work was measured using the “2-pin method” where the “pins” were initially cast-in brass plates with dimensions equal to the sides of the mortar cubes (i.e. 40 mm x 40 mm), **Fig. 1**. The resistance of the specimen was measured by applying an alternating DC current of 1mA at a frequency of 1 kHz, using a PC-controlled R-meter and was calculated based on the measured voltage at the time of current interruption. The resistance measurement was performed after interruption of the current for approx. 30 min and surface drying of the mortar cubes. The electrical resistivity was calculated using Ohm’s Law: $\rho = R \cdot A / l$, where ρ is the resistivity in Ohm.m, R is the resistance in Ohm, A is the cross-section of the mortar cube in m², and l is the length in m. The detailed experimental method can be found in (Susanto *et al.* 2017).

3. Results and discussion

3.1 Compressive strength of hardened (28 day-cured) mortar

Mechanical properties are a key indicator for the performance of cement-based materials, reflecting concrete quality. There are several factors that affect the strength of cement-based materials, such as: water/cement ratio, cement type, admixtures and curing conditions, including humidity, temperature and ageing (time) (Mehta *et al.* 2001, Nehdi *et al.* 2011). In this work, compressive strength tests were performed to quantify the influence of stray current flow on the mechanical properties of 28-day cured mortar specimens with different w/c ratio (i.e. 0.5 and 0.35), subsequently conditioned in varying external medium and conditions (i.e. H₂O immersed, Ca(OH)₂ immersed and sealed).

As can be observed in **Fig. 2(a)** to **Fig. 2(d)**, irrespective of external medium and conditioning, as well as irrespective of w/c ratio, the compressive strength for all specimens increased with time. This was as expected and consistent with the ongoing cement hydration with ageing. The increase in compressive strength for the control, water treated specimens (designation control H₂O in **Fig. 2**), was in the range of 11.5% to 13.8% higher for the group of lower w/c ratio 0.35, compared to those of w/c ratio 0.5. Higher compressive strength

Fig. 2 Compressive strength with conditioning from 0 to 84 days (hydration age of 28 to 112 days) for 28 days-cured mortar specimens of w/c ratio 0.5 and 0.35 in partly (a, c) and fully (b, d) submerged in H₂O and Ca(OH)₂ conditions - comparison of control and “under current” regimes.

was recorded for the control specimens conditioned in calcium hydroxide (specimens designation control CH in Fig. 2(a) to Fig. 2(d)), compared to all analogical cases in water. This result was also expected, since in the absence of concentration gradient, leaching-out would not be relevant, hence mechanical and micro-structural properties are expected to improve.

The highest current density level (1 A/m^2) resulted in the largest effect on compressive strength: for water-conditioned groups, Fig. 2(b, d), the lowest compressive strength was recorded for group $1 \text{ A/m}^2\text{-H}_2\text{O}$, while for Ca(OH)_2 specimens – the opposite result of highest compressive strength for the 1 A/m^2 , CH groups was recorded, Fig. 2(b, d).

The effect of w/c ratio and stray current can be judged in parallel for each conditioning environment by comparing the difference in compressive strength between the specimens “under current” and the relevant control cases at identical age. For specimens half or partly submerged in calcium hydroxide solution (Fig. 2),

only positive effect as aforementioned (increased compressive strength) was recorded for specimens “under current”. For the water-conditioned groups, a reversed trend was observed.

Figure 3 depicts a comparison of compressive strength for 28 days-cured mortar specimens of w/c ratio 0.5 and 0.35 in partly and fully submerged in H_2O (Fig. 3a,b). The difference in compressive strength between control and “under current” specimens (based on averaged values and considering standard deviation) for all water-treated specimens is presented in Fig. 3(c), where the simultaneous effect of varying stray current density and varying w/c ratio can be also observed. Should be noted, that although a difference in compressive strength between 2 and 10 MPa is in general considered to be insignificant on a global scale, the depicted variation, more importantly, the trend of observed changes, clearly differentiates the performance per regime and case.

At hydration age of 28 days (or conditioning time “0”

Fig. 3 Comparison of compressive strength with conditioning from 0 to 84 days for 28 days-cured mortar specimens of w/c ratio 0.5 and 0.35 in partly (a) and fully (b) submerged in H_2O ; c) variation in compressive strength values between “under current” regimes in water conditions (1/2 and full immersed) and the relevant control cases (i.e. $\text{MPa} = (\text{MPa}_{\text{control}} - \text{MPa}_{\text{under current}})$).

days), the compressive strength for all cases was almost identical (circle-indicated region in **Fig. 3**). For the half-immersed specimens, which are also cases where the stray current was at the lowest tested level of 10 mA/m^2 , the specimens of lower w/c ratio (1/2 10 mA , w/c 0.35, **Fig. 3c**) presented a more pronounced reduction in compressive strength, compared to the identically conditioned mortar of higher w/c ratio (1/2 10 mA , w/c 0.5, **Fig. 3c**). At the end of the test, there was no appreciable difference between these groups of specimens, both showing a compressive strength decrease with ca. 2 MPa, compared to the relevant control cases, **Fig. 3(c)**, **Fig. 2(a, c)**.

For fully immersed conditions, the same level of current density and identical environmental conditions, the higher w/c ratio (0.5) resulted in improvement of properties at initial stages (circle-indicated region in **Fig. 3c**). With age and treatment, a reduction in strength was observed, more pronounced for the specimens of lower w/c ratio 0.35 (**Fig. 3(c)**, middle section of the plot). At the end of the test, most specimens reached a similar variation with respect the relevant control cases, ca. 2 MPa reduced strength was observed (rectangular-indicated region in **Fig. 3c**).

Throughout conditioning and at the end of the test, the most detrimental effect of stray current was observed in the case of specimens, subjected to the highest current density level of 1 A/m^2 and lower w/c ratio of 0.35 i.e. the lower w/c ratio accelerated the negative effect of stray current in aged specimens – arrow marked regions in **Fig. 3c**. Although the difference as such (in absolute values) is not significant on a global scale, the trend clearly shows that stray current can be affecting a mature matrix, of lower pore water volume, to a larger extent. This has to be bared in mind for practical applications, where presumably optimized mix design (lower w/c ratio) and optimized curing (hardened concrete) are generally considered to better withstand negative external influences.

The effect of leaching-out due to enhanced migration in conditions of stray current and concentration gradient

with the external environment can be better visualized if the results for compressive strength of water-conditioned specimens are compared to results for sealed specimens.

The evolution of compressive strength for sealed mortar specimens of w/c ratios 0.5 and 0.35, at identical hydration ages in control and under current regimes of 100 mA/m^2 and 1 A/m^2 , are depicted in **Fig. 4**. The plot includes the above discussed results for fully submerged in water conditions in view of a direct comparison. As expected, and in line with the previous discussion, the effect of ion/water migration on mechanical properties is obviously related to the water-conditioned specimens (**Fig. 3**, specimens “R full” and “1A full” at both w/c 0.35 and 0.5), reflected in decreasing compressive strength in time due to stray current. The negative effect (reduction in compressive strength) is more evident for the lower w/c ratio in fully submerged conditions (**Fig. 4b**). In contrast, the compressive strength in sealed conditions was only increased. The positive effect in sealed conditions is more evident at higher w/c ratio (**Fig. 4a**).

The results on mechanical performance for all specimens and conditions are fully supported by microstructural investigation and results on development of the bulk matrix in time, which will be discussed in the next sections.

3.2 The effect of curing and stray current on pore structure (identical w/c ratio 0.5, varying curing time i.e. 24h and 28 days)

MIP tests were performed to quantify the simultaneous effect of curing age, w/c ratio and stray current flow on the microstructural changes of mortar specimens. The complete study on 24h cured specimens of w/c ratio 0.5 for all conditions and stray current regimes has already been reported (Susanto *et al.* 2017). The results at the first and final tested time intervals for the 24h cured specimens are only partly discussed here in comparison to 28 days cured mortar, for comparative purposes and to elucidate the effect of curing on pore network development.

Fig. 4 Compressive strength development in 28-days cured mortar specimens, comparison for fully submerged in water and sealed conditions, w/c ratio 0.5 (a) and w/c 0.35 (b).

The actual MIP results for all specimens subject to discussion in the following sections 3.2.1, 3.2.2 and 3.3 are presented for the hydration age of 112 days (Figs. 5, 8, 11, 13). For an easy comparison (in view of the large amount of recorded MIP data), the full range of MIP results for all discussed specimens are summarized and discussed with relevance to Figs. 6, 7, 9, 12, 14.

3.2.1 Water immersed conditions

The MIP results for half and fully immersed water-conditioned specimens at hydration age of 112 days are shown in Fig. 5(a-d) as a comparison of: control and 10 mA/m² current regime of the 24h and 28 days cured specimens (Fig. 5a, b) and control, 100 mA/m² and 1A/m² of 24h and 28 days cured specimens (Fig. 5c, d).

Porosity and pore size (including critical pore size) were derived from MIP as previously introduced – the former, based on the cumulative intrusion vs pore size curves (Fig. 5a, c), the latter i.e. pore size distribution and critical pore size – based on the differential curves (Figs. 5b, d). As aforementioned, for the sake of simplicity and clear comparison the MIP results for the rest of the discussed hydration ages, together with the 112 days results, are summarized in Figs. 6 and 7.

As previously commented, the microstructural properties of mortar are strongly affected by calcium ions

leaching, which would be relevant when a concentration gradient with the external environment is present e.g. as for the mortar specimens in partly and fully submerged in water conditions in this work. Additionally, the leaching-out process would be enhanced in conditions of stray current, which results from ion and water migration, together with diffusion-controlled ion and water transport. As can be seen from the results in Figs. 5 to 7, porosity increased with increasing the level of stray current for both half (Figs. 5a, b and 6) and fully (Figs. 5c, d and b) immersed in water specimens. This was relevant for both groups of 24-h and 28-days cured mortar.

For specimens cured for 24-h only, in half immersed in water conditions and at hydration age of both 28 and 112 days (Fig. 6), porosity increased with 0.64% at 28 days of age and ca. 1.35% at 112 days of age due to current flow at the level of 10 mA/m² (specimens 10 mA, 24h), compared to control conditions (specimens R 1/2, 24h). For the 28 days-cured specimens, the difference in porosity due to stray current of 10 mA/m² in half-immersed in water conditions was not as significant at 112 days of age (Fig. 6). Increased critical pore size for the 10mA regime, compared to the control case was observed (Fig. 6, specimen 10 mA, 28d), hence coarsening of the matrix due to stray current was relevant. At

Fig. 5 MIP-derived porosity and pore size distribution at 112 days of age for specimens of identical 0.5 w/c ratio but different curing time intervals i.e. 24h cured and 28 days cured specimens: (a, b) half-immersed in water control and 10 mA/m² regime (c, d) fully immersed in water, 100 mA/m² and 1A/m² regimes.

the age of 140 days both porosity and pore size for the 28 days cured specimens maintained similar to those derived for 112 days (Fig. 6).

For fully immersed in water conditions and larger current densities (Fig. 7), the difference in recorded porosity and pore size values for the 28days-cured specimens at 84 days of conditioning (112 days of age) and 112 days of conditioning (140 days of age) was more obvious. The results showed a 1.4% increase for the 100 mA and 1.79 % increase for the 1A regime, compared to control conditions at 112 days of age and almost equal values at 140 days of age. A difference in critical pore size was also observed, similar to half-immersed conditions, where the highest critical pore size was relevant for the highest current density level of 1 A/m² (Fig. 7, specimen 1A-28d), corresponding to the higher porosity in this condition. If these results are compared to the derived values for 24h-cured specimens subjected to the same levels of stray current and consid-

ering identical hydration age of 112 days (Figs. 5c, d), a significantly different pore network development was observed for the 24h-cured groups (Figs. 5c, d and 7), where porosity increased significantly at 28 days, with variation of > 3% due to stray current. At the age of 112 days, the effect was less obvious, but still more pronounced compared to the 28 days-cured specimens i.e. 0.35% increase for the 100 mA and 1.65% increase for the 1A regime, compared to the control conditions in the 24h-cured series (Figs. 5c, d, and 7). Critical pore size remained larger as well, if compared to that of the 28days-cured specimens at equal hydration age (e.g. 112 days, Fig. 7).

What can be stated is that for equal w/c ratio (0.5 in this case) the effect of stray current on bulk matrix microstructural properties is affected by the curing of the cement-based material i.e. 28 days curing results in less pronounced negative effect on porosity and pore size. In contrast, 24h curing only, equivalent to a fresh matrix on

Fig. 6 Porosity (column; solid column for 24h cured) and critical pore size (symbol, "cr.pore" in legend) at hydration ages of 28 days, 112 days and 140 days for 24h and 28 days cured mortar of identical w/c ratio 0.5, **half immersed in H₂O**. The plot presents a comparison of control cases (designation R for both 24h and 28d cured) and those, subjected to 10 mA stray current (designation 10 mA for both 24h and 28d cured).

Fig. 7 Porosity (column; solid column for 24h cured) and critical pore size (symbol, "cr.pore" in legend) at hydration ages of 28 days, 112 days and 140 days for 24h and 28 days cured mortar of identical w/c ratio 0.5, **fully immersed in H₂O**. The plot presents a comparison of control cases (designation R for both 24h and 28d cured) and those, subjected to 100 mA/m² and 1 A/m² stray current (designation 100mA and 1A for both 24h and 28d cured).

site in practical conditions, will be affected more significantly by stray current flow. This is linked to enhanced ion and water migration in the bulk matrix in fresh state, leading to leaching-out of alkali ions and matrix degradation (Susanto *et al.* 2013, 2017), especially pronounced at early ages. In contrast, although negatively influenced as well, a more mature and adequately cured matrix of identical w/c ratio, would be less affected. This is at least to the level of stray current flow in the range of 10 mA to 1 A/m², as applied in this work. This dependence, however, is not straightforward, as will be demonstrated in the following sections.

3.2.2 Calcium hydroxide immersed conditions

The MIP results for 112 days hydration age for specimens conditioned in Ca(OH)₂ are presented in Fig. 8. The summarized results for all reported hydration ages, including 112 days of age, are depicted in Figs. 9 and 10.

For half immersed in calcium hydroxide conditions, for the 28 days-cured groups at 112 days of conditioning (Figs. 8a, b and 9), 0.9% decrease in porosity was recorded due to current density of 10 mA/m², compared to the control specimens in this group. For fully immersed conditions in the same group (Figs. 8c, d and 10), the porosity decreased with 0.4 % and 0.6% for the current

levels of 100 mA/m² and 1A/m², respectively. In contrast, for the 24 hours-cured specimens, at conditioning age of 28 days porosity decreased with ca. 1% for the 10mA regime, compared to control cases (Fig. 9). In the same 24h-cured group, for fully immersed in calcium hydroxide condition (Figs. 8c and d), porosity decreased with ca.1.5% and ca. 2% for 100 mA/m² and 1 A/m², respectively (Fig. 10), compared to control conditions. In other words, for Ca(OH)₂-conditioned specimens, irrespective of curing time and regime of conditioning, densification only of the bulk matrix was observed for all cases. The effect of all current levels was in fact only positive, enhanced ion and water transport exerting raised cement hydration, which was more pronounced for the 24h-cured group, because of the fresh mortar state. If the 28days-cured specimens are considered, elevated ion and water transport would be also at hand, judged by the lower porosity of the specimens as derived in all conditions, mostly pronounced for the highest current density level of 1 A/m² (Figs. 8 and 10). The as recorded porosity changes for 28 days-cured specimens at w/c ratio 0.5 and for all conditions (Figs. 5-10) are well in line with the recorded compressive strength development (Figs. 2 to 4). The strength of the mortar specimens increased with a decrease in porosity

Fig. 8 MIP-derived porosity and pore size distribution at 112 days of age for specimens of identical 0.5 w/c ratio but different curing time intervals i.e. 24h cured and 28 days cured specimens: (a, b) half-immersed in Ca(OH)₂ control (R1/2) and 10 mA/m² regime (10mA) (c, d) fully immersed in Ca(OH)₂ control (Rfull), 100 mA/m² (100 mA) and 1A/m² (1A) regimes (designation 24h and 28d refers to the respective curing time).

and vice versa, as also stated by other authors (Mehta *et al.* 2001; Roy *et al.* 1993; Lian *et al.* 2011).

What can be concluded is that when curing conditions and stray current are judged in parallel for identical in w/c ratio specimens (identical mortar mixtures and identical external medium), the factor determining performance is the level of stray current. The curing conditions (24h or 28 days as in this case) are only important at early age and when concentration gradient with the external environment is present (as in water conditions). With increased maturity of the cement matrix, the initially different curing conditions are not a decisive factor for the potentially negative effect of stray current, but rather the external medium and level of current will be decisive parameters. This is reflected by pore network coarsening of both 24h-cured and 28 days-cured water-conditioned specimens at hydration age of > 100 days and subjected to higher current density (> 100 mA/m² in this test).

3.3 The effect of w/c ratio (0.5 and 0.35) in stray current conditions on pore structure development of equally cured (hardened) bulk matrix (28 day-cured mortar)

Water-to-cement ratio has an important role for strength and durability of concrete. In general, higher w/c ratio results in an increase of capillary porosity (Sahu *et al.* 2004; Powers *et al.* 1958), subsequently reduced strength. **Figures 11 and 13** show the MIP results for 28 days-cured mortar at the hydration age of 112 days for the specimens discussed in this section i.e. w/c ratio 0.35 and 0.5, water and Ca(OH)₂ immersed. **Figures 12 and 14** depict the summarized information from MIP results for all discussed time intervals, including the 112 days of age.

For partly immersed in water conditions and level of current density 10 mA/m², the effect of w/c ratio together with the stray current effect, was not significant (**Fig. 11a, b and 12**). As can be observed in **Fig. 12(a)**, similar porosity was recorded for the control cases (R ½

Fig. 9 Porosity (column; solid column for 24h cured) and critical pore size (symbol, “cr.pore” in legend) at hydration ages of 28 days, 112 days and 140 days for 24h and 28 days cured mortar of identical w/c ratio 0.5, **half immersed in Ca(OH)₂**. The plot presents a comparison of control cases (designation R for both 24h and 28d cured) and those, subjected to 10 mA stray current (designation 10 mA for both 24h and 28d cured).

Fig. 10 Porosity (column; solid column for 24h cured) and critical pore size (symbol, “cr.pore” in legend) at hydration ages of 28 days, 112 days and 140 days for 24h and 28 days cured mortar of identical w/c ratio 0.5, **fully immersed in Ca(OH)₂**. The plot presents a comparison of control cases (designation R for both 24h and 28d cured) and those, subjected to 100 mA/m² and 1 A/m² stray current (designation 100mA and 1A for both 24h and 28d cured).

specimens 0.5 and 0.35) at 112 days and only a slight densification of the matrix was relevant for the w/c 0.35 group at 140 days. Critical pore size was also similar for the control groups, irrespective of w/c ratio (Figs. 11a, b and 12a). For the “under current” specimens (10 mA) of w/c ratios at both 0.5 and 0.35, coarsening was observed, compared to the relevant control case, slightly more pronounced for the 0.5 group at the stage of 112 days. Critical pore size remained similar, as for the control groups.

For fully immersed in water specimens (Figs. 11c, d and 12b), a larger effect of the w/c ratio was observed, also in combination with the already larger current density levels of 100 mA/m² and 1 A/m². Similarly to half immersed in water conditions, the control cases presented a slight difference due to w/c ratio, reduced critical pore size and 0.3 % lower porosity at 140 days for the mortar of w/c 0.35, compared to that of w/c 0.5 at the same age. The effect of stray current was not significant at later hydration ages, except the slightly lower porosity and pore size for the 0.35 w/c ratio specimens (Fig. 12b). Coarsening of the pore network was evident in both 0.5 and 0.35 cases, more pronounced for the

specimens of w/c ratio 0.5 (Fig. 12b), although a family of pores around 1 micrometer appeared to be pronounced for the 0.35 w/c ratio group in fully immersed conditions and in 100 mA and 1A current regimes (Fig. 11d). The critical pore size, however, for both groups of w/c ratio 0.5 and 0.35 remained similar per case/condition, reduced for the 0.35 w/c ratio group (Fig. 11d).

The most pronounced (negative) effect of stray current in these (fully immersed in water) conditions was recorded for the highest current density level of 1 A/m² and the higher w/c ratio of 0.5 (Figs. 11d and 12b). However, the almost equal values for the 1 A/m² case in both series of w/c 0.35 and w/c 0.5 at identical hydration age, suggests that the negative effect of stray current does not depend significantly on w/c ratio and/or curing conditions. The above statements are well in line with the recorded compressive strength values (Fig. 2). Moreover, this correlation of results even suggests that stray current can result in enhanced reduction of global mechanical properties in specimens of lower w/c ratio, because of restricted cement hydration in a lower pore water volume, which would otherwise positively coun-

Fig. 11 MIP-derived porosity and pore size distribution at 112 days of age for 28 day-cured mortar specimens: (a, b) **half-immersed in water** specimens as a comparison of w/c ratio 0.5 and 0.35 in control (R1/2) and 10 mA/m² current regime (10mA); (c, d) **fully immersed in water**, 28-day cured specimens of w/c ratio 0.35 and 0.5 in control (R full), 100 mA/m² (100 mA) and 1 A/m² (1A) current regime.

terbalance ion and water migration. In fact, a more significant reduction in compressive strength was as observed for the lower w/c ratio of 0.35, as already commented in Section 3.1 (Fig. 3). Consequently, optimum curing and improved concrete mixture would only delay, but not prevent the influence of stray currents in practical situations.

In contrast to partly or fully immersed in water conditions, the results for all specimens conditioned in calcium hydroxide, present only densification of the pore network i.e. positive effect of the stray current, irrespective of w/c ratio and/or current density levels. Porosity and critical pore size for all specimens reduced with time and with the application of stray current in both partly and fully immersed conditions (Figs. 13 and 14). Slightly lower values were observed for the series of w/c ratio 0.35, compared to those for the series of w/c ratio 0.5. The largest effect of stray current was observed for the highest current density level of 1 A/m^2 . These results are in line with the mechanical performance of these series of specimens, where a gradual increase of compressive strength values was observed at all time intervals and for all specimens in calcium hydroxide environment (Fig. 2). As previously discussed, in conditions where concentration gradient between the pore water and external environment is avoided, the stray current effect, up to the level of the hereby tested current densities, is only positive.

3.4 Electrical resistivity of 28-day cured mortar in condition of stray current flow

As above discussed, the stray current flow through mortar specimens in different environmental conditions, led to a change in porosity and pore size distribution of the bulk matrix. This was expected to reflect also in changed electrical properties of the specimens. According to Archie's law (Archie 1942), the electrical resistivity is mainly influenced by porosity and moisture. Electrical resistivity is reported to be an indicator of the interconnectivity and tortuosity of the pore network (Andrade *et al.* 2000). As also reported, concrete electrical resistivity depends on pore volume and pore size distribution (Lakshminarayanan *et al.* 1992). Furthermore, well known is that interconnected pores would have influence on electrical resistivity, since these are the pore pathways determining transport properties (i.e. diffusion and permeability). In general, although not a straightforward relationship, the electrical properties of concrete i.e. electrical resistivity, would increase with a decrease in porosity.

Figures 15, 16 present the evolution of electrical resistivity of the 28 days-cured mortar specimens, partly and fully submerged in water and calcium hydroxide solution. A comparison is also made between different w/c ratios, i.e. 0.5 and 0.35.

As can be observed, from 28 days until ca. 40 days of conditioning (or ca. 70 days of age), the electrical resistivity

Fig. 12 Porosity (column; solid column for w/c 0.5) and critical pore size (symbol, "cr.pore" in legend) at hydration ages of 112 days and 140 days for 28 days cured mortar of different w/c ratio (0.5 and 0.35), **half immersed in H₂O (a) and fully immersed in water (b)**. The plot a) presents a comparison of control cases (designation R 1/2) and those, subjected to 10 mA/m^2 (designation 10 mA); b) compares control cases (designation R full) with 100 mA/m^2 (designation 100 mA) and 1 A/m^2 (designation 1A).

tivity for all specimens increased with time, irrespective of w/c ratio and conditions. This is logic and as expected, reflecting the maturity development of the cement matrix with time of hydration. After 40 to 55 days of conditioning, the trend of change was a stabilization for $(\text{Ca}(\text{OH})_2)$ treated specimens (Figs. 15, 16 – open symbols, designation CH) and decrease of electrical resistivity for water treated specimens (Fig. 15, 16, solid symbols, designation H_2O).

Increase or stabilization of electrical resistivity values follows the logic of continuous cement hydration with time and conditioning when no detrimental factors are involved. This would be the case for sealed specimens, where water balance is maintained within the volume of the matrix only, and there is no exchange or loss of humidity in external environment (e.g. for sealed specimens, higher electrical resistivity was recorded for the lower w/c ratio (0.35) compared to w/c ratio 0.5 (results not shown, since these are reported in detail in Susanto *et al.* (2017)).

The “turning point” of resistivity development - decrease of electrical resistivity for the water-conditioned specimens after longer treatment (> 50 days), for both partly immersed (Fig. 15) and fully immersed (Fig. 16),

was obviously related to the previously discussed pore network alterations - coarser pore structure, as observed for water treated specimens. The negative effect of stray current can be well observed in these cases, reflected by the lowest electrical resistivity for specimens, subjected to the highest current density levels (Fig. 16). As can be also observed in both Fig. 15 and Fig. 16, the negative effect of stray current was not determined by w/c ratio i.e. was relevant at comparable levels in both cases of w/c 0.35 and w/c 0.5, despite the lower amount of pore water at the w/c ratio of 0.35, compared to that of w/c ratio 0.5.

The electrical resistivity of mortar specimens in calcium hydroxide solution increased with time and with the application of stray current. For the specimens of w/c ratio 0.5 (Figs. 15a and 16a) an increase only of electrical resistivity were observed for the specimens in 10 mA/m^2 , 100 mA/m^2 and 1 A/m^2 regimes, compared to control conditions. Similar trend was recorded for the mortar of w/c 0.35, (Figs. 15b and 16b), in identical current regimes and if compared to the relevant control cases. What can be also observed for all specimens, conditioned in $\text{Ca}(\text{OH})_2$, irrespective of w/c ratio and current density levels, is that stabilization of the resistiv-

Fig. 13 MIP-derived porosity and pore size distribution at 112 days of age for 28 day-cured mortar specimens: (a, b) **half-immersed in $\text{Ca}(\text{OH})_2$** specimens as a comparison of w/c ratio 0.5 and 0.35 in control (R1/2) and 10 mA/m^2 current regime (10mA); (c, d) **fully immersed in $\text{Ca}(\text{OH})_2$** , 28-day cured specimens of w/c ratio 0.35 and 0.5 in control (R full), 100 mA/m^2 (100 mA) and 1 A/m^2 (1A) regime.

ity values per condition was relevant after 60 days of conditioning, specifically for fully immersed conditions (Fig. 16).

4. Concluding remarks

This paper reports on the influence of stray current flow on hardened cement-based materials of varying w/c ratio and the resulting consequences on compressive strength and pore network development. The following conclusions can be summarised:

- The compressive strength of 28 day-cured mortar is

affected by stray current flow, depending on the environmental conditions and the level of current density. When concentration gradient with the external environment is not present (i.e. alkali ions leaching-out is avoided), compressive strength generally increases due to enhanced ion and water migration in the bulk matrix, consequently leading to enhanced cement hydration. This effect is irrespective of w/c ratio. However, in conditions where concentration gradient exists (e.g. water, soil as external medium), the stray current promotes additional ion and water migration towards the external medium. Therefore the effect is negative

Fig. 14 Porosity (column; solid column for w/c 0.5) and critical pore size (symbol, "cr.pore" in legend) at hydration ages of 112 days and 140 days for 28 days cured mortar of different w/c ratio (0.5 and 0.35), *half immersed in Ca(OH)₂* (a) and *fully immersed in Ca(OH)₂* (b).

Fig. 15 Electrical resistivity of 28-day cured mortar specimens, *partly immersed* in water and calcium hydroxide, conditioned from 28 to 112 days: a) specimens of w/c ratio 0.5; b) specimens of w/c ratio of 0.35.

Fig. 16 Electrical resistivity of 28-day cured mortar specimens, *fully immersed* in water and calcium hydroxide, conditioned from 28 to 112 days: a) specimens of w/c ratio 0.5; b) specimens of w/c ratio of 0.35.

in the long term, leads to a reduction in mechanical properties and coarser microstructure.

- The largest negative effect of stray current was observed in the case of specimens, subjected to the highest current density level (1 A/m^2) and lower w/c ratio of 0.35 i.e. the lower w/c ratio accelerated the negative effect of stray current in aged specimens. This has to be bared in mind for practical applications, where presumably optimized mix design (lower w/c ratio) and optimized curing (28 days curing and continuous cement hydration without water loss) are generally considered to better withstand negative external influences.
- The microstructural development (porosity and pore size), as well as the evolution of electrical properties (electrical resistivity) were well in line and supporting the evolution of mechanical properties. Coarsening of the pore structure and decrease in electrical resistivity were observed for higher levels of current density and in water medium as external environment. In contrast, densification of the pore network and increase in electrical resistivity were relevant for alkaline medium as external environment.
- The correlation of results for 28 day-cured mortar in conditions of stray current and varying external medium shows that a properly cured and relatively more mature cement matrix will be also susceptible to the effect of stray currents. This conclusion elucidates the previously posed hypothesis, that a mature matrix could potentially withstand the effect of stray current, if compared to a relatively fresh and non-mature specimens (as the 24h-cured mortar (Susanto *et al.* 2017). Furthermore, lower w/c ratio would not account for elimination or substantial reduction of the stray current effects. The dominating factors for the reduced performance of cement-based materials in conditions of stray current remain the level of current density and the presence or absence of concentration gradient with the external environment. Stray current at levels $> 100 \text{ mA/m}^2$ would lead to negative effect on material properties, which would be substantial in the presence of concentration gradient with the external medium.

Acknowledgements

The first author acknowledges the financial support from Directorate General of Higher Education Ministry of Education Republic of Indonesia (DIKTI) with grant number 1375.32/D4.4/2010 for supporting his PhD project in TU Delft.

References

- ACI Committee, (1982). "Hot weather concreting." ACI 305R-77, ACI, Detroit, Mich.
- ACI Committee, (1981). "Standard practice for curing concrete." ACI 308-81, ACI, Detroit, Mich.
- Al-Ani, S. H., Mokdad, A. and Al Zaiwary, K., (1988). "The effect of curing delay on concrete in hot weather." *Materials and Structures*, 21(3), 205-212.
- Andrade, C., Alonso, C., Arteaga, A. and Tanner, P., (2000). "Methodology based on the electrical resistivity for calculation of reinforcement service life." *Fifth CANMET/ACI International Conference*, 899-915.
- Andrade, C., Castellote, M. and d'Andrea, R., (2011). "Chloride aging factor of concrete measured by means of resistivity." *Proceedings of the XII-international conference on durability of building materials and components*, Porto, Portugal.
- Archie, G. E., (1942) "The electrical resistivity log as an aid in determining some reservoir characteristics." *Transactions of the American Institute of Mining and Metallurgical Engineers*, 146, 54-62.
- Atkins, P. W., (1990). "Physical chemistry" Oxford: Oxford University Press.
- Aylott, P. J., Cotton, I. and Charalambous, C. A., (2013). "Impact and management of stray current on DC rail systems." CHAPCIS Intertek, United Kingdom.
- Bentz, D. P. and Garboczi, E. J., (1999). "Effects of cement particle size distribution on performance properties of Portland cement-based materials." *Cement and Concrete Research*, 29(10), 1663-1671.
- Bertolini, L., Carsana, M. and Pedferri, P., (2007). "Corrosion behaviour of steel in concrete in the presence of stray current." *Corrosion Science*, 49(3), 1056-1068.
- Bredenkamp, S., Kruger, D. and Bredenkamp, G. L.,

- (1993). "Direct electric curing of concrete." *Magazine of Concrete Research*, 45(162), 71-74.
- Castellote, M., Andrade, C. and d'Andréa, R., (2009). "The use of resistivity for measuring aging of chloride diffusion coefficient." *Proceedings RILEM TC 211-PAE International Conference - Concrete in Aggressive Aqueous Environments*, Toulouse.
- Charalambous, C. A. and Aylott, P., (2014). "Dynamic stray current evaluations on cut-and-cover sections of DC metro systems." *IEEE Transactions on Vehicular Technology*, 63(8), 3530-3538.
- Galsgaard, F. and Nielsen, L. V., (2006). "AC/DC interference corrosion in pipelines." Summary Report by MetriCorr., The Danish Gas Technological Centre.
- Hewlett, P. C., (2003). "Lea's chemistry of cement and concrete." New York: John Wiley & Sons.
- Indian Standard, (2000). "Plain & reinforced concrete-Code of practice." IS 456: 4th revision, p. 27.
- Katz, A. J. and Thompson, A. H., (1986) "Quantitative prediction of permeability in porous rock." *Physical Review B*, 34, 8179-8181.
- Koleva, D. A., Hu, J., Fraaij, A. L. A., Stroeve, P., Boshkov, N. and van Breugel, K., (2006). "Cathodic protection revisited: Impact on structural morphology sheds new light on its efficiency." *Cement and Concrete Composites*, 28(8), 696-706.
- Koleva, D. A., De Wit, J. H. W., van Breugel, K., Lodhi, Z. F. and Ye, G., (2007). "Investigation of corrosion and cathodic protection in reinforced concrete II. Properties of steel surface layers." *Journal of the Electrochemical Society*, 154(5), C261-C271.
- Koleva, D. A., Guo, Z., van Breugel, K. and De Wit, J. H. W., (2009). "The beneficial secondary effects of conventional and pulse cathodic protection for reinforced concrete, evidenced by X - ray and microscopic analysis of the steel surface and the steel/cement paste interface." *Materials and corrosion*, 60(9), 704-715.
- Koleva, D. A., Guo, Z., van Breugel, K. and de Wit, J. H. W., (2010). "Microstructural properties of the bulk matrix and the steel/cement paste interface in reinforced concrete, maintained in conditions of corrosion and cathodic protection." *Materials and corrosion*, 61(7), 561-567.
- Kurumisawa, K. and Nawa, T., (2016). "Electrical conductivity and chloride ingress in hardened cement paste." *Journal of Advanced Concrete Technology*, 14(3), 87-94.
- Lakshminarayanan, V., Ramesh, P. S. and Rajagopalan, S. R., (1992). "A new technique for the measurement of the electrical resistivity of concrete." *Magazine of Concrete Research*, 44(158), 47-52.
- Lian, C., Zhuge, Y. and Beecham, S., (2011). "The relationship between porosity and strength for porous concrete." *Construction and Building Materials*, 25(11), 4294-4298.
- McCarter, W. J., Butler, A., Chrisp, T. M., Emerson, M., Starrs, G. and Blewett, J., (2001). "Field trials on concrete monitoring sensors." *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, 146(3), 295-305.
- Mehta, P. K. and Monteiro, P. J. M., (2001). "Concrete: Microstructure, properties and materials." McGraw-Hill.
- Nehdi, M. and Soliman, A. M., (2011). "Early-age properties of concrete: overview of fundamental concepts and state-of-the-art research." *Proceedings of the Institution of Civil Engineers - Construction Materials*, 164, 57-77.
- Neville, A. M., (1995). "Properties of concrete." 4th and final Ed., London: Longman.
- Page, C. L., Short, N. R., Holden, W. R., (1986). "The influence of different cements on chloride-induced corrosion of reinforced steel." *Cement Concrete Research*, 16, 79-86.
- Powers, T. C., (1958). "The physical structure and engineering properties of concrete." PCA Res. Dept. Bull., 90.
- Ritter, H. L. and Drake, L. C., (1945). "Pore-size distribution in porous materials, Pressure porosimeter and determination of complete macropore-size distributions." *Industrial and Engineering Chemistry*, 17, 782-786.
- Roy, D. M. and Idorn, G. M., (1993). "Concrete microstructure." Strategic Highway Research Program, National Research Council, Washington, DC.
- Sahu, S., Badger, S., Thaulow, N. and Lee, R. J., (2004). "Determination of water-cement ratio of hardened concrete by scanning electron microscopy." *Cement & Concrete Composites*, 26, 987-992.
- Susanto, A., Koleva, D. A., van Breugel, K. and van Beek, C., (2017). "Stray current-induced development of cement-based microstructure in water-submerged, Ca(OH)₂-submerged and sealed conditions." *Journal of Advanced Concrete Technology*, 15, 244-268.
- Susanto, A., Koleva, D. A., Copuroglu, O., van Beek, C. and van Breugel, K., (2013). "Mechanical, electrical and microstructural properties of cement-based materials in conditions of stray current flow." *Journal of Advanced Concrete Technology*, 11, 119-134.
- Susanto, A., Koleva, D. A. and van Breugel, K., (2017). The influence of stray current on the maturity level of cement-based materials. In: *Concrete Durability*. Springer International Publishing, 57-82.
- Troxell, G. E., Davis, H. E. and Kelly, J. W., (1968). "Composition and properties of concrete." 2nd ed. New York: McGraw-Hill.
- Wang, K., Cable, J. K. and Zhi, G., (2002). "Investigation into improved pavement curing materials and techniques, Part 1 (Phases I and II)." Center for Portland Cement Concrete Pavement Technology, Iowa State University.
- Washburn, E. W., (1921). "The dynamics of capillary flow." *Physical Review*, 17(3), 273-283.
- Ye, G., (2003). "Experimental study and numerical

simulation of the development of the microstructure and permeability of cementitious materials.” Thesis (Ph.D.), Delft University of Technology.
Kim, Y.-Y., Lee, K.-M., Bang, J.-W. and Kwon, S.-J.,

(2014). “Effect of W/C ratio on durability and porosity in cement mortar with constant cement amount.” *Advances in Materials Science and Engineering*, Vol. 2014, ID 273460.