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Penetration of corrosion products and corrosion-induced cracking in reinforced cementitious materials: Experimental investigations and numerical simulations

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ABSTRACT

This paper describes experimental investigations on corrosion-induced deterioration in reinforced cementitious materials and the subsequent development and implementation of a novel conceptual model. Reinforced mortar specimens of varying water-to-cement ratios were subjected to current-induced corrosion (10, 50, and 100 μA/cm^2). X-ray attenuation measurements and visual investigations provided both qualitative and quantitative information on the penetration of solid corrosion products into the surrounding cementitious matrix. X-ray attenuation measurements provided time- and location-dependent concentrations of corrosion products averaged through the specimen thickness. Digital image correlation (DIC) was used to measure corrosion-induced deformations including deformations between steel and cementitious matrix as well as formation and propagation of corrosion-induced cracks. Based on experimental observations, a conceptual model was developed to describe the penetration of solid corrosion products into capillary pores of the cementitious matrix. Only capillary pores within a corrosion accommodating region (CAR), i.e. in close proximity of the steel reinforcement, were considered accessible for corrosion products. The conceptual model was implemented into a FEM based cracking model and compared to experimental results provided in the literature and obtained from DIC measurements.

1. Introduction

The development of numerical tools to describe initiation, see e.g. [1,2], and propagation, see e.g. [3,4], of reinforcement corrosion including corrosion-induced deterioration has gained momentum in the past decades. In particular, finite element method (FEM) [5–7], analytical [8,9], and empirical approaches [10] to model and predict corrosion-induced deterioration in reinforced concrete structures have been developed in vast amounts.

While the results of developed models are typically in good agreement with experimental data, two crucial factors must be highlighted. First, corrosion rates applied during experimental tests used for validation of the proposed models, e.g. [11,12], far exceeded corrosion rates reported for actual structures [13]. Second, more recent approaches introduced a factor, i.e. the ‘porous’ or ‘diffusion’ zone (see e.g. [6,14]), which is commonly used to fit experimental data without direct observation or verification of the actual size. The terms ‘porous’ or ‘diffusion’ zone are omitted in this paper and replaced with the more accurate term, corrosion accommodation region (CAR). The CAR describes a region of concrete around the reinforcement, which can accommodate expansive corrosion products delaying stress development in the concrete. This region has a major influence on the predicted time to crack initiation and the crack propagation [6,14]. Recently, the X-ray attenuation measurement technique was demonstrated to provide non-destructive means for monitoring movements of corrosion products, observations on the formation and propagation of corrosion-induced cracks, and a direct determination of the CAR size [15]. During an initial study to investigate the applicability of X-ray attenuation measurements, a corrosion current density of 250 μA/cm^2 was applied, which exceeds natural corrosion rates. Penetration of corrosion products in cementitious materials likely depends on the corrosion current density, among other factors.

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Hence, for a realistic determination of the CAR, realistic corrosion current densities shall be investigated.

This paper presents X-ray attenuation and digital image correlation (DIC) measurements of the time-dependent development of corrosion products and corrosion-induced cracks in reinforced cementitious materials. Results of an experimental study are presented in which the influence of corrosion current density and water-to-cement ratio (w/c) on the CAR as well as formation and propagation of corrosion-induced cracks was studied. Corrosion current densities used in the experimental study ranged from 10 to 100 $\mu A/cm^2$ (corresponding to a corrosion rate of approximately 0.12–1.16 mm/year), where 10 $\mu A/cm^2$ has been reported as a realistic corrosion current density for actual structures subjected to corrosion, see e.g. [13]. X-ray attenuation measurements were used to investigate the influence of varying corrosion current density and w/c on the development of corrosion products and the CAR. Digital image correlation (DIC) was applied to monitor corrosion-induced deformations between the corroding steel rebar and the surrounding cementitious matrix. The experimental results of X-ray attenuation and DIC measurements were used to develop a conceptual model to describe the penetration of corrosion products into the available capillary pore space of the cementitious matrix. Finally, the conceptual model was implemented in a finite element based cracking model and results of numerical simulations were compared to experimental observations obtained from DIC measurements and provided in the literature.

2. Experimental approach

2.1. Materials and specimen preparation

Aalborg Rapid® Portland cement (CEM I 52.5 N) was used for the preparation of all mortar specimens containing 50% fine aggregates by volume. Specimens with varying w/c (0.3, 0.4, and 0.5) were prepared for accelerated corrosion testing. Plasticizer (Sika Viscocrete-2300HE) was added to specimens with 0.3 (0.5% by weight of cement) and 0.4 (0.3% by weight of cement) w/c to maintain a similar workability as for specimens with a w/c of 0.5. No chlorides were added to the mix, as corrosion was induced applying an electrical current as described in the following section. As reinforcement, a smooth steel rod with a diameter of 10 mm was embedded in the centre of the $10 \times 10 \times 50$ cm^3 prisms. Mortar samples were prepared using a standard mortar mixer and mixing procedures [16], placed in forms, and consolidated by rodding and vibrating. After casting the prisms were stored in molds under a plastic sheet in laboratory conditions (i.e. 20 ± 2 °C) and then demolded. Upon demolding, the prisms were stored for additional six days under water at 20 ± 2 °C. Finally, the 50 cm long prisms were cut in 2.3 cm lengths using a water-cooled concrete saw and a lead wire was attached to the steel rebar to allow for accelerated corrosion testing. For specimens that were later used for DIC, a stochastic black and white speckle pattern was applied (using spray paint) on one side of the specimens.

2.2. Accelerated corrosion

For X-ray attenuation measurements, nine specimens (three different w/c and three different corrosion current densities) were connected to direct current (DC) regulators to allow for accelerated corrosion testing. For DIC measurements, individual specimens were connected to a DC regulator to enforce corrosion and monitor corrosion-induced deformations. The experimental setup used is illustrated in Fig. 1 (for DIC measurements only one specimen was tested at time). To impress an electrical current through the counter electrode (ruthenium/iridium mixed metal oxide activated titanium mesh) a commercial DC regulator was used. Electrical connection between the working (reinforcement) and counter electrodes was realised placing the test specimens in tap water (no chlorides were added to the solution). The water level was maintained at approximately 1 cm below the steel bar and ponds were refilled daily. Three current densities were used for each w/c investigated including 10, 50, and 100 $\mu A/cm^2$ (see Table 1). Specimens of identical current densities were connected in series (see Fig. 1) to ensure the same corrosion current density was applied to all specimens of a test series.

2.3. X-ray attenuation measurement technique

A GNI X-ray facility [17,18] located at the Technical University of Denmark was used to monitor the time-dependent development of corrosion products (and subsequent formation and propagation of cracks in reinforced mortar specimens). Fig. 2a illustrates the facility, consisting of a polychromatic X-ray source, a 252×256 pixel X-ray camera, and a programmable three-axis motion frame for moving the source and camera, which are housed in a shielded, environmentally controlled chamber. The X-ray source excitation settings used were a voltage of 80 keV and a current of 75 μA. The X-ray source was automatically ramped up to these settings over a 120 s 'warm-up' period and the X-ray source was allowed to stabilize for 60 s prior to recording images. A single measurement consisted of 60 X-ray camera images recorded with an integration time of one second each (i.e. 60 s integration time). The intensities measured by individual pixels from the 60 images were summed. So-called dark current images (i.e. X-ray camera images recorded while X-ray source is turned off) recorded prior to all X-ray measurements were subtracted from the measured intensities. For each specimen, X-ray measurements were taken three times in its initial state (i.e. a total of 180 images), before any corrosion current was applied. After commencing the accelerated corrosion testing, X-ray measurements were recorded every 4, 12 and 24 h for the 100, 50, and 10 $\mu A/cm^2$ specimens, respectively. Testing was terminated when specimens showed extensive corrosion-induced damage. Additional information on the X-ray

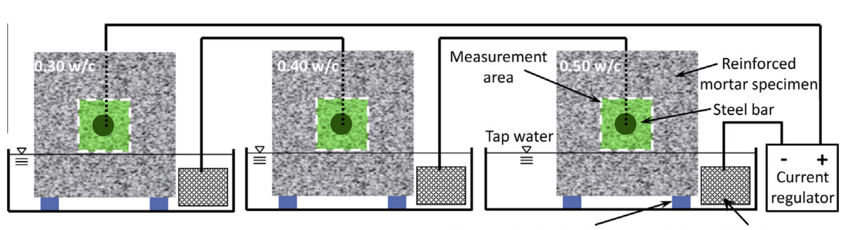

Fig. 1. Experimental setup for accelerated corrosion testing by impressed current, 'measurement region' indicates area captured by X-ray attenuation and digital image correlation measurements.