ARTICLE IN PRESS

Cement and Concrete Research xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

Moisture ingress in cracked cementitious materials

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ARTICLE INFO

Keywords:
X-ray attenuation measurement technique
B. Microcracking
C. Transport properties
E. Modelling

ABSTRACT

Wedge split test specimens were conditioned to a relative humidity of 50%, deformed to various damage states, and exposed to liquid water. Water ingress was monitored using x-ray attenuation measurements and compared to numerical predictions. The transport model accounts for the damage state using the cracked hinge model and a simplified approach whereby a crack is considered to consist of two distinct parts: 1) a coalesced crack behaving as a free surface for moisture ingress, and 2) an area of isolated micro cracks behaving as bulk material. Comparison of experimental and model results shows the simplified crack geometry approach applied in the transport model is capable of predicting the ingress of moisture and influence of cracks. The model was found to underestimate the vertical extent of moisture ingress in the largest CMOD samples (0.20 and 0.40 mm), which was likely due to instability of the large cracks in these samples.

1. Introduction

The state and distribution of moisture in (reinforced) cementitious materials is of great importance for the assessment and prediction of many deterioration mechanisms, such as reinforcement corrosion, alkali silica reaction, carbonation, freeze thaw, *etc.*, see *e.g.* [1–4] Thus, the prediction of the moisture distribution as a result of the interaction of cementitious materials with the environment, *i.e.* moisture ingress, has been subject of numerous experimental and numerical studies, see *e.g.* [5–7]. While research on the governing transport phenomena related to moisture ingress, such as diffusion, permeability, capillary suction, has received a great deal of attention, see *e.g.* [8–10], the impact of cracks on the moisture ingress in cementitious materials is studied to a far less extent. In practice, however, cracks can be found in nearly all reinforced concrete structures originating, among others, from hygral or thermal shrinkage and/or mechanical loading. Nevertheless, studies concerning the impact of cracks on moisture ingress in cementitious materials have generally concluded that cracks facilitate rapid ingress of moisture as well as aggressive substances, such as chlorides, carbon dioxide, *etc.*, [11–17] and subsequently may reduce the service life of reinforced concrete structures.

To enable realistic predictions of the moisture ingress in cementitious materials, numerical tools need to be tested against and calibrated with experimental data. Experimental investigations and data must thereby concern both the spatial resolution of moisture ingress and a realistic representation of the crack morphology, in cases where moisture ingress in cracked materials is studied. While several studies have demonstrated that various techniques are applicable to obtain desired spatial resolution for moisture ingress, limited studies conducted experimental investigations to determine the moisture ingress in cementitious materials with realistic crack morphologies. Commonly, artificial cracks are introduced to study the moisture ingress by means of sawing or casting, see *e.g.* [13]. While such studies may be used to represent idealized cases for numerical simulations, the predictive capabilities of such approaches may be limited for actual structures.

The focus of this study was to provide experimental data of moisture ingress in cementitious materials with load-induced crack morphologies. The impact of loading and cracking on the moisture ingress was investigated for steel fibre reinforced concrete (0.25% fibre by volume) subjected to the wedge splitting test. Before exposure to moisture, test specimens were loaded or cracked to desired load levels and crack widths, respectively, and conditioned at a relative humidity of 50% for 1 year. Upon conditioning, the test specimens were exposed to liquid water and the moisture ingress monitored by means of repeated x-ray attenuation measurements over a period of 24 h. In addition to the experimental investigations, predictions of a numerical model are presented in this study. The model is based on a liquid conductivity approach and accounts for the impact of cracks by means of a simplified crack geometry to predict the moisture ingress in cementitious materials. Although, the concept of moisture ingress through a simplified

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https://doi.org/10.1016/j.cemconres.2018.08.009
Received 11 March 2018; Received in revised form 20 July 2018; Accepted 30 August 2018

Please cite this article as: Michel, A., Cement and Concrete Research, https://doi.org/10.1016/j.cemconres.2018.08.009

crack geometry is demonstrated in this study for steel fibre reinforced concrete, it can be expected that the approach is also valid for cementitious materials without (steel) fibre reinforcement, when crack width and length are determined by fracture mechanical approaches. The analysis of crack propagation in reinforced concrete, at a structural level, is commonly performed by means of cohesive crack models [18]. Although these models only provide limited information on width and length of cracks, integration of moisture ingress and simplified crack geometries presents a considerable step forward in state-of-the-art service life predictions for reinforced concrete structures. Within the modelling approach, the crack is thereby divided into two distinct regions: *i*) a coalesced crack region, which behaved as a free surface for moisture ingress and *ii*) a non-coalesced crack region, for which similar transport properties as for the bulk material are assigned.

2. Experimental investigations

To investigate the impact of cracks on the moisture transport in cementitious materials, wedge split test (WST) specimens were prepared, conditioned, cracked, and exposed to liquid water. Experimental investigations covered mechanical testing and non-destructive x-ray attenuation measurements. Mechanical testing consisted of a splitting load applied to WST specimens *via* a rigid wedge using crack mouth opening displacement (CMOD) control. Initially, three samples were cracked to a CMOD of 1.8 mm, to allow for the estimation of materials properties using the cracked hinge model (CHM) as described in Section 2.3, while the remaining samples were loaded or cracked to 70% and 90% of peak load, peak load, 0.10 mm, 0.15 mm, 0.20 mm, and 0.40 mm CMOD. After loading/cracking of the WST specimens, aluminum tape was used to seal all specimen sides except the top surface, which provided a pond for exposure to liquid water *via* the cast-in recess and cut notch. The CMOD was measured directly above the cut notch, at the bottom of the specimen's recess.

In addition to the mechanical testing, non-destructive x-ray attenuation measurements were undertaken to determine the moisture content in the loaded or cracked WST specimens during ponding with liquid water. A 25 × 25 mm^2 x-ray camera captured repeatedly images of 15 locations, providing data from an 80 × 55 mm^2 region of the WST specimens. The measured region was centered horizontally with the notch and vertically the measurement area started approximately 10 mm above the specimen bottom. Fig. 1 illustrates both the cross section of the WST specimen and approximate locations where x-ray camera images were captures.

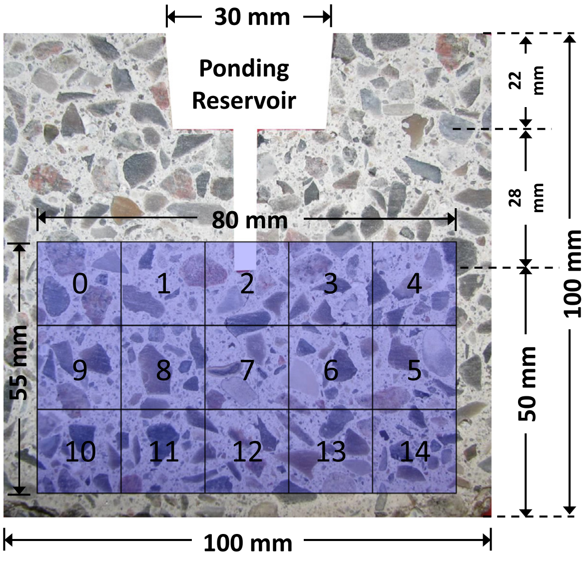

Fig. 1. The WST specimen geometry and details on location of x-ray images. Please note: not to scale.

For convenience, the specimen identifications used throughout are based on the CMOD or load condition associated with each specimen. It is however important to note that the actual crack widths affecting the ingress of water are smaller than the CMOD due to the tapered nature of cracks formed in the WST specimen (this is discussed in detail in Section 4 and Table 3).

2.1. Materials and specimen preparation

Aalborg White® Portland cement was used to prepare the WST specimens and had an estimated Bogue composition of 78.8% C_3S, 10.5% C_2S, 4.9% C_3A, 1.0% C_4AF, 0.6% MgO, 2.1% SO_3, and a Na_2O equivalent alkali content of 0.19%. Aggregates used were washed Class E 0–4 mm sea-sand and Class A 4–8 mm sea-gravel (in accordance with [19]). The water-to-cement ratio was 0.50 with a cement content of 330 kg/m^3, 764 kg/m^3 fine aggregates, 1099 kg/m^3 coarse aggregates (71.5% aggregate by volume), and 19 kg/m^3 steel fibers (0.25% fibre by volume). The steel fibers had a length of 12.5 mm, diameter of 0.4 mm, elastic modulus of 200 GPa, and tensile strength of 1300 MPa. The concrete was mixed using a standard pan mixer with a 120 l capacity. The fine and coarse aggregate were first mixed dry for 1 min, followed by 3 min mixing with one third of the mixing water. Mixing was stopped for 2 min prior to adding and mixing the cement for 1 min. The remaining water was then added and mixing continued for 3 min after addition of water, during which time the steel fibers were added. The mixer was then opened and the pan and blades were scraped, followed by 1 min additional mixing. Upon mixing, concrete was placed and compacted by combined rodding and vibration in customized wedge split test (WST) specimen molds yielding a 100 × 100 × 100 mm^3 prism with a recess on the specimen's top; as shown in Fig. 1. After casting, specimens were stored in laboratory conditions (*i.e.*, 18 ± 2 °C) covered with wet burlap and plastic sheets for 24 h. Subsequently, the specimens were sealed in multiple layers of plastic at 20 ± 2 °C and cured for another 6 days before placing the still sealed samples in an oven at 45 ± 2 °C until samples reached a maturity age of 1 year. After accelerated curing, specimens were unsealed, a 28 mm notch (with a width of 4.5 mm) was cut resulting in a height of 50 mm (see Fig. 5(a)), and halved yielding two 50 mm thick specimen. All cuts were made using a water-cooled concrete saw. After cutting, specimens were conditioned at 50 ± 3% relative humidity and 20 ± 2 °C for at least 1 year.

2.2. X-ray attenuation measurement technique

To determine the moisture content in the loaded/cracked WST specimens upon exposure to liquid water, non-destructive x-ray attenuation measurements were repeatedly undertaken. For this purpose, a GNI x-ray attenuation measurement system located at the Technical University of Denmark [20] was used, as shown in Fig. 2(a). The x-ray measurement system consisted of a polychromatic x-ray source and a 25 × 25 mm^2 x-ray camera housed in a programmable, moveable frame. X-ray source energy settings of 110 keV and 15 μA were used for all measurements.

Commonly, the composite system shown in Fig. 2(b) is used to derive Eq. (1) [20–22], which relates the reduction in x-ray photons passing through an initially conditioned specimen, I_{dry}, caused by ingress of liquid water, I_{wet}, to the change in moisture content, Δw

$$\Delta w = -\frac{\rho_w}{\mu_{eff,w}\, t}\, ln\left(\frac{I_{wet}}{I_{dry}}\right) \tag{1}$$

where ρ_w is the density of water, $\mu_{eff,w}$ the effective attenuation coefficient of water (*i.e.*, the attenuation coefficient of water as measured through 50 mm WST specimens), and t the specimen thickness. Results published in [23] indicate that the material type and thickness of the