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Can Electrical Resistance Tomography be used for imaging unsaturated moisture flow in cement-based materials with discrete cracks?

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ABSTRACT

Previously, it has been shown that Electrical Resistance Tomography (ERT) can be used for monitoring moisture flow in undamaged cement-based materials. In this work, we investigate whether ERT could be used for imaging three-dimensional (3D) unsaturated moisture flow in cement-based materials that contain discrete cracks. Novel computational methods based on the so-called absolute imaging framework are developed and used in ERT image reconstructions, aiming at a better tolerance of the reconstructed images with respect to the complexity of the conductivity distribution in cracked material. ERT is first tested using specimens with physically simulated cracks of known geometries, and corroborated with numerical simulations of unsaturated moisture flow. Next, specimens with loading-induced cracks are imaged; here, ERT reconstructions are evaluated qualitatively based on visual observations and known properties of unsaturated moisture flow. Results indicate that ERT is a viable method of visualizing 3D unsaturated moisture flow in cement-based materials with discrete cracks.

1. Introduction

The resistance of concrete structures to the ingress of moisture and aggressive ions is commonly considered a measure of their durability [1,2]. Cracking creates preferential pathways for moisture and aggressive ions to penetrate the bulk material and decrease the durability of concrete structures [3–5]. To understand the role of cracks in moisture flow, and durability in general, imaging methods are needed.

Several imaging methods that exploit electromagnetic radiation have been used to study moisture movement in concrete and other cement-based materials with discrete cracks. Roels et al. [6] used 2D X-ray radiography to monitor moisture penetration in brick with discrete cracks to validate moisture flow simulations. Roels and Carmeliet [7] later used a 2D X-ray radiography technique to study homogeneous and non-homogeneous material with micro-scale discrete cracks. Pour-Ghaz et al. [8,9] corroborated numerical simulations of unsaturated moisture flow with 2D X-ray radiography to assess moisture movement in a saw-cut. Kanematsu et. al [10] used neutron radiography to image moisture flow in bending-induced cracks; they showed that the moisture content of the cementitious materials surrounding the cracks significantly affects the rate of moisture ingress. Carmeliet et al. [11] measured crack distribution in concrete using 3D microfocus X-ray Computed Tomography (CT) and monitored water distribution resulting from infiltration of water in a variable aperture crack. Fukuda et al. [12] investigated self-healing of cracks in low-permeability concrete using X-ray CT imaging. Recently, Li et al. [13] used neutron radiography to monitor water uptake in simulated concrete pavement joints, showing that entrained air saturates more slowly than the gel porosity. These examples demonstrate that cracking and moisture movement in cementitous material (and porous material, in general) can be captured using imaging modalities based on electromagnetic radiation. Moreover, imaging based on electromagnetic radiation has provided significant insights into the role of cracks in moisture flow in cracked material. However, these imaging methods are often impractical because they are generally limited to small geometries (on the order of a few centimeters), have very high energy demands, require large facilities (such as a nuclear reactor in the case of neutron imaging), may be invasive, and are often expensive to perform [14,15].

On the other hand, electrically-based methods generally do not have such testing limitations. In particular, Electrical Impedance Spectroscopy (EIS) has been previously used to monitor unsaturated moisture flow in cement-based materials. In the majority of previous research studies utilizing EIS, electrode pairs were embedded in cement-based material, and pairwise impedance measurements

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between electrodes were performed. For example, McCarter and coauthors [16–19] embedded electrodes at different vertical depths to detect the depth of the moisture ingress. In the approach proposed by McCarter et al. [19], the maximum rate of impedance change (as a function of time) was assumed to indicate the arrival of the water front at the height of an electrode pair. In addition, Rajabipour et al. [20] developed an analytical function using finite element simulations to relate pairwise impedance measurements to the location of "moisture front." However, the localization of the water front based on the pairwise impedance measurements is possible only if the water front is approximately horizontally aligned, i.e., the water flow is one-dimensional (1D). If the moisture content varies in three dimensions, interpretation of pairwise EIS measurements is a challenging task.

In contrast to EIS, Electrical Resistance Tomography (ERT) reconstructs the spatial distribution of the internal electrical conductivity resulting from moisture ingress without the need of *ad hoc* experimental and/or analytical calibrations. Research reported in [21–23] was perhaps the first attempt to monitor 2D moisture flow in cement-based material using ERT. More recently, ERT was used to monitor 1D ion and moisture flow in concrete slabs [24]; the ERT reconstructions were corroborated with Ground Penetrating Radar (GPR). In [14] ERT reconstructions of two-dimensional (2D) moisture flow in cement paste were compared with neutron radiography images, showing a good qualitative agreement between the two imaging methods. Further, in [25] ERT was shown to be capable of qualitatively imaging 3D moisture flow in large dimensional objects made of cement-based materials, and in [26], an approach for quantifying the moisture content in cement-based materials using ERT was proposed; the results were in good agreement with simulations of moisture flow.

In all the above-cited ERT studies, moisture flow was imaged in cement-based materials that were undamaged. The cracking induces an additional difficulty to moisture flow monitoring on the basis of electrical measurements: Cracks are complex 3D structures with high conductivity contrasts – unsaturated cracks being essentially non-conductive inclusions and water-filled cracks being highly conductive. In such conditions, the inference of moisture distribution would be virtually impossible with EIS. ERT, on the other hand, carries more information on the 3D distribution of the electrical conductivity than EIS, and furthermore, previous research has demonstrated the potential of ERT for localizing non-conductive cracks in cement-based materials [27,28]. However, due to the diffusive nature of ERT, its spatial resolution is usually low [29], and it has a limited ability to simultaneously image inclusions that feature different electrical properties. Hence, the capability to separately detect unsaturated cracks in a uniform background and moisture flow in uncracked material does not guarantee the ability to monitor moisture flow in cracked materials. Therefore, this paper seeks for an answer to the question: Can ERT be used for monitoring 3D unsaturated moisture flow in cement-based materials with discrete cracks?

To address the above question, a series of experiments is carried out, with physically-simulated cracks and with discrete cracks that are generated by split-tensile loading. The physically-simulated cracks have known geometries, which enable a comparison between ERT images and results of moisture flow simulations. Because the specimens used in the experiments are large, neutron and X-ray tomography are not suitable methods for corroboration [8,25,26,30]; thus, the ERT reconstructions of samples with split-tensile loading induced cracks are evaluated only by visual comparison with the photographs of the specimen.

In the following sections, material and sample preparation are discussed, a brief review of the ERT scheme is provided, a method of simulating unsaturated moisture flow is presented, and finally results are reported and discussed.

2. Materials and sample preparation

2.1. General

For determining the feasibility of ERT for monitoring moisture flow in cracked cement-based material, a total of five specimens were prepared. Two specimens had physically-simulated cracks and three had loading-induced discrete cracks. The physically-simulated cracks included a cylindrical through-crack penetrating the entire height of the specimen and a plate-like crack penetrating 2/3 of the specimen height; these specimens are shown in Fig. 1a and b, respectively. The three specimens with discrete cracks were damaged using split-tension loading and are shown in Fig. 2. Two of these specimens had non-metallic fibers to reduce the crack widths and decrease the rate of water ingress. The remaining specimen did not include fibers.

2.2. Materials

All of the specimens were made of ordinary Portland cement (Type I) and fine aggregate (natural river sand, fineness modulus = 2.63). The water-to-cement ratio (w/c) was 0.60 and the volumetric aggregate content was 40.0%. It should be noted that in selecting this mortar mixture, we ignored the contribution of the Interfacial Transition Zone (ITZ). Percolation of ITZ, which may happen at a higher aggregate volume fractions, may enhance the transport properties [31]. The low aggregate content and high water-to-cement ratio was used to increase the capillary porosity of the mortar, thereby increasing the rate of capillary transport in the material. This effectively decreased the experimentation time, which would be longer using a mortar mixture with a higher aggregate content and a lower w/c ratio. While all specimens used the same cement and aggregates, two of the specimens were cast with 0.2% (by volume) non-conductive nylon fiber reinforcement (directly replaced aggregate volume, to ensure identical cement paste content in all specimens) to reduce crack widths resulting from split-tension loading. The nylon fibers were 1.9 cm long (aspect ratio of 70) and had a tensile strength of 966 MPa. The mixing was carried out according to ASTM C192-06 [32].

To create the physically-simulated cracks (shown in Fig. 1a and b), inclusions were inserted in two of the 10.20× 20.30 cm cylindrical specimens immediately after casting. To construct the specimen with the cylindrical through-crack, a rod (diameter 1.0 cm) was inserted through the top of the mold lid. The rod, and the induced cylindrical crack, penetrated from top to bottom of the specimen. For the specimen with the plate-like crack, a PVC plate inclusion of dimensions 0.8 cm × 6.6 cm × 6.6 cm was inserted into top of the specimen. After 4 h, the inserts were removed from the specimens and the specimen molds were completely resealed using new plastic lids. The cylinders were then demolded after 24 h and cut in half using a wet saw

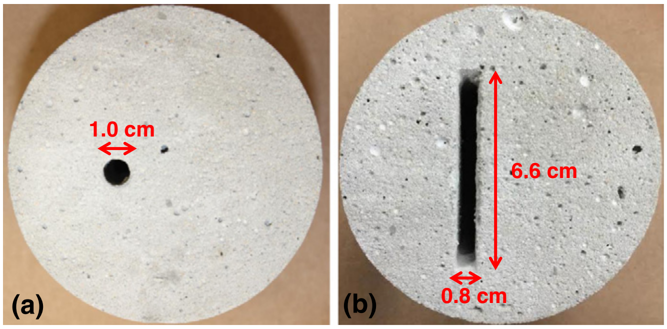

Fig. 1. Specimens with physically-simulated cracks; (a) specimen with cylindrical through-crack and (b) specimen with plate-like crack.

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