Cement and Concrete Research 69 (2015) 10–18

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Electrical resistance tomography to monitor unsaturated moisture flow in cementitious materials

Milad Hallaji [a], Aku Seppänen [b], Mohammad Pour-Ghaz [a,*]

[a] Department of Civil Construction and Environmental Engineering, North Carolina State University, Raleigh, NC 27695, USA
[b] Department of Applied Physics, University of Eastern Finland, Kuopio, Finland

ARTICLE INFO

Article history:
Received 18 April 2014
Accepted 12 November 2014
Available online 20 December 2014

Keywords:
Concrete (E)
Electrical Resistance Tomography (ERT)
Image Analysis (B)
Transport Properties (C)

ABSTRACT

Traditionally the electrically-based assessment of the moisture flow in cement-based materials relies on two- or four-point measurements. In this paper, imaging of moisture distribution with electrical resistance tomography (ERT) is considered. Especially, the aim is to study whether ERT could give information on unsaturated moisture flows in cases where the flow is non-uniform. In the experiment, the specimens are monitored with ERT during the water ingress. The ERT reconstructions are compared with neutron radiographs, which provide high resolution information on the 2D distribution of the moisture. The results indicate that ERT is able to detect the moisture movement and to show approximately the shape and position of the water front even if the flow is nonuniform.

1. Introduction

The durability of reinforced concrete structures is related to the ability of concrete to impede the ingress of water and aggressive agents (e.g., [1,2]). Therefore, the water transport rate in concrete is often used as a measure of the durability. Advanced methods have been developed to monitor the moisture movement in unsaturated cement-based materials including nuclear magnetic resonance (NMR) spectroscopy [3–5], methods based on attenuation of electromagnetic radiation (e.g. gamma-ray [6–8], X-ray [9,7,10–13] and neutron [14–21] imaging), and electrically-based methods [22–27].

Each of the aforementioned methods has advantages and limitations. While NMR, gamma-ray, X-ray, and neutron imaging have a high resolution, they are generally limited to small specimens (from a few millimeters to a few centimeters, depending on the equipment and source intensity) due to large energy requirements for imaging large specimens. In addition, gamma-ray, X-ray and neutron imaging are invasive methods and are mainly limited to laboratory due to the required facilities. For example, neutron imaging (radiography/tomography) requires a neutron source, such as a nuclear reactor. Electrically-based methods, in contrast, have a low spatial resolution, but they are noninvasive, inexpensive and rapidly performed.

Various electrically-based methods, such as electrical impedance spectroscopy (EIS) [26,28] and single frequency alternating current measurements [28], have been used for monitoring unsaturated flow in cement-based materials. In the majority of previous studies, a set of electrode pairs was embedded in the cement-based material, and impedances between pairs of electrodes were measured. For example, McCarter et al. [22,24,27–29] monitored water ingress in concrete specimens by measuring the impedance between electrode pairs embedded at different depths. They showed that the impedance measured decreases significantly as the water front enters the "influence zone" of the electrode pair. Due to the diffusive nature of the electric current, however, the impedance between the electrodes changes even by the moisture content change far from the height of the electrode pair. Consequently, the inference of the water front location based on such measurements is not a straightforward task.

To estimate the location of the water front based on pairwise impedance measurements, both experimental and numerical calibration strategies have been proposed. McCarter et al. [22,24,29] proposed a method in which the rate of impedance change is monitored as a function of time, and the arrival of the water front at the height of the electrode pair is taken as the time at which the rate of impedance change is at maximum. Rajabipour et al. [26] derived an analytical function based on finite element simulations to relate the impedance between embedded electrode pairs to the water front position. It is noted that the impedance measurements from horizontally aligned electrode pairs can provide estimates for the water front location only if the water front is approximately horizontally aligned, i.e., the water flow is one-dimensional (1D). This assumption is not always valid; the water flow can be non-uniform for example due to the spatial variation of the porosity.

Electrical resistance tomography (ERT) is an imaging modality which could provide a robust tool for monitoring the moisture flow in concrete. In ERT, the three-dimensional (3D) distribution of the

* Corresponding author. Tel.: +1 919 515 2235; fax: +1 919 515 7908.
E-mail address: mpourghaz@ncsu.edu (M. Pour-Ghaz).

http://dx.doi.org/10.1016/j.cemconres.2014.11.007
0008-8846/

electrical resistivity is imaged using a set of current injections and electrode potential measurements. ERT has been used for monitoring the water infiltration in soil [30–34]. Buettner et al. [35,36] have also studied the feasibility of ERT for monitoring the water ingress in concrete. Stacey [37] applied ERT for monitoring moisture movement in Berea sandstone. While the studies of Buettner and Stacey showed the potential of ERT for monitoring the moisture flow in concrete and sandstone, the results of ERT were not corroborated by other techniques. Recently, duPlooy et al. [38] used ERT to monitor (essentially) 1D water ingress in concrete slabs. One face of each slab was exposed to water for 23 days, and ERT measurements were performed using electrodes attached to the wetted side of the slab. The results were in agreement with destructive tests and the estimates from electrical capacimetry and ground penetrating radar.

The objective of this study is to investigate whether ERT could give feasible information on the distribution of moisture in cases where the water flow is non-uniform. To this end, ERT imaging of moisture flow is experimentally compared with high resolution neutron radiography. Both a horizontally uniform (1D) and a nonuniform (2D) water source are used, resulting in different shapes of the water front; in the 2D case, the water front is not even approximately horizontally aligned.

2. Materials and methods

Two cement paste specimens were used in the experiment. A water reservoir was mounted on top of each specimen. ERT and neutron radiography measurements were simultaneously carried out during water ingress. The entire top surface of the first specimen was exposed to water, while in the second specimen the water reservoir covered only about one third of the top surface. The aim of this setting was to induce a 1D water flow in the first specimen and a 2D flow in the second one.

Photographs of the two specimens 60 min after the addition of water are shown in Fig. 1. The dark surface areas indicate the wetted regions, and qualitatively the difference between the two flows is clear: in the first case (Fig. 1a) the water front is nearly horizontal, whereas in the second case (Fig. 1b) water forms a curved plume which grows radially. Although the photograph in Fig. 1a (and especially the neutron radiographs in Section 3) shows that the water front in the first specimen is not exactly horizontal, we refer to this test case as the 1D flow case and the corresponding water source as the 1D source. Respectively, the attributes of the second specimen (Fig. 1b) are referred to as the 2D flow and the 2D source.

2.1. Materials

To facilitate simultaneous ERT and neutron radiography measurements, several constraints had to be addressed. First, the neutron imaging requires a nuclear reactor laboratory, and the allowable time for carrying out the experiment in this facility was limited. To reduce the duration of the test, highly porous cement paste was used to facilitate a rapid water ingress. The rapid moisture movement, on the other hand, constrains the time allowed for acquiring a neutron image: if the neutron exposure time is long, the moisture distribution changes considerably during the exposure and causes artifacts in neutron images. To reduce the neutron exposure time, relatively thin samples were used in the experiment. Furthermore, the initial moisture content of the material had to be high enough; the electrical resistivity of a very dry cementitious material is high, and this may cause problems in ERT imaging [39]. It is also noted that enough contrast in conductivity, and hence in moisture content, is necessary for the water movement to be detectable by ERT. The exact threshold for this contrast depends on many factors including the pore size distribution of the material, sensitivity of and the noise in measurements, and sample and electrode size. Establishing this contrast ratio requires experimental and computational investigations. Finally, many setup accessories were made of Teflon or aluminum, because they are almost “transparent” to neutrons and thus do not cause artifacts in radiographs.

2.1.1. Cement paste material

Specimens used in this work were made of type I ordinary portland cement (OPC, Type I) with a water-to-cement ratio (w/c) of 0.60. The plain cement paste and high w/c were selected in order to produce a highly porous material. ERT measurements can be performed on concrete and mortar as well [38–40]. However, the feasibility of ERT to monitor moisture movement in concrete needs to be experimentally investigated in the future.

2.1.2. Sample preparation

The cement paste was mixed according to ASTM C305 and was cast in a 7.6 × 7.6 × 30.5 cm steel mold. The steel mold rested on a 7.6 cm × 30.5 cm face during casting. After casting, the mold was wrapped in a wet cloth and a layer of plastic. The specimen was demolded after 18 h. To reduce the porosity gradient from top to bottom of the specimen (due to possible segregation in the high w/c cement paste) a 0.50 cm thick layer from the top of the prism was cut using wet saw and discarded. Next, the cement paste prism was sliced into 1.37 cm

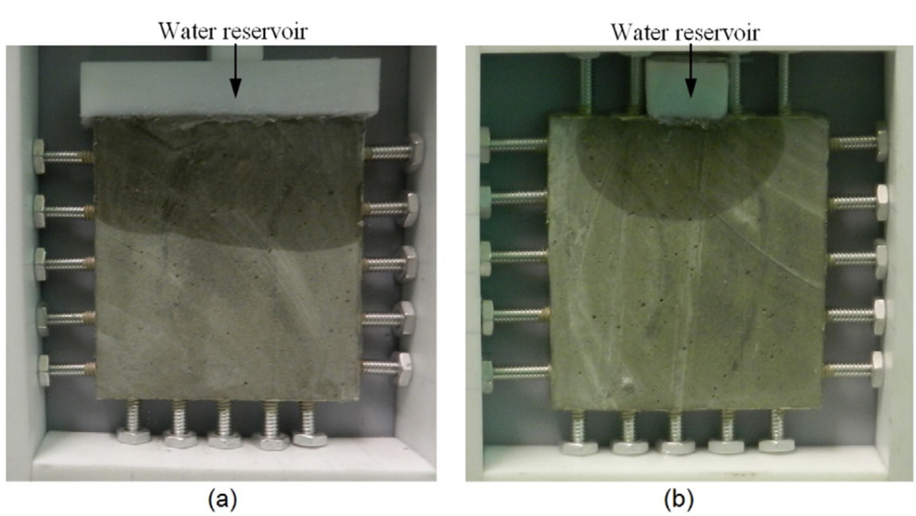

Fig. 1. Photographs of the specimens 60 min after adding water: a) specimen with 1D water source; b) specimen with 2D water source.