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A comparison of methods to evaluate mass transport in damaged mortar

Farnam Ghasemzadeh, Reza Rashetnia, Danny Smyl, Mohammad Pour-Ghaz*

Dept. of Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, NC, USA

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ABSTRACT

The service life of reinforced concrete (RC) structures is directly influenced by the transport properties of concrete. These transport properties are adversely affected by the presence of cracks. Therefore, for accurate service life estimation of RC structures the effect of cracks on mass transport needs to be understood and quantified. To quantify the effect of cracks, different measurement methods have been developed. In this paper, we compare different mass transport measurement methods for quantifying the effect of damage, and investigate which method is more sensitive and provides the most information on the effect of damage.

In this work, damage was induced by freeze-thaw in mortar specimens. Mass transport properties were measured using electrical resistivity, rapid chloride permeability, sorptivity, drying, air permeability, water permeability, and desorption isotherm. The results indicate that the measured effect of damage depends on the mechanisms of transport used in the measurement technique, and therefore, different measurement techniques do not necessarily provide the same measure of the effect of damage. The water and air permeability are comparatively more sensitive to the presence of damage.

1. Introduction

Distributed micro-cracking, referred to as damage hereafter, is commonly observed in concrete structures. Damage may result from different deterioration processes, such as freeze-thaw and alkali silica reaction. The presence of damage can significantly alter the transport properties of concrete, adversely affecting the service life of structures. Therefore, in order to account for the effect of damage on the service life of structures, its effects on mass transport need to be quantified. Different methods have been developed to measure and quantify the transport properties of cement-based materials. Many of these methods utilize different transport mechanisms and, as such, provide different measures of the effect of damage on mass transport properties [1]. We pose the following research questions: (i) how do different measurement techniques show the effect of damage on mass transport? (ii) Which transport measurement methods are more sensitive to the presence of damage? In line with these questions, we experimentally compare different mass transport measurement techniques and produce laboratory results that enable us to answer these questions.

Broadly, cracking in cement-based materials can be regarded as discrete cracking or distributed cracking (damage). Researchers have investigated mass transport in cement-based materials containing discrete cracks in fundamental works, such as the following: Aldea et al. (1999) [2], who found that discrete cracks (40–200 μm crack widths) have a more profound effect on water permeability than chloride permeability. Rodriguez (2001) [3] showed that chloride diffusion increases in material with saw-cut simulated cracks and that the lateral diffusion of chloride along the crack wall is nearly constant. Rodriguez and Hooten (2003) [4] found that the depth of chloride penetration increases in cracked samples, irrespective of the presence of mineral admixtures. Picandet et al. (2009) [5] found that crack permeability increases with the cube of crack opening displacement in specimens with discrete cracks in the range of 20–177 μm. They also concluded that the use of fibre reinforcement increases the tortuosity of cracks. Pour-Ghaz et al. (2009) [6,7] investigated the role of saw-cut geometry as an idealized physical model of discrete cracks using X-Ray radiography and numerical simulations; their results indicated that the geometry of cracks significantly affects the ratio of the rate of unsaturated flow parallel and perpendicular to the crack. Akhavan et al.

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* Corresponding author. Dept. of Civil, Construction and Environmental Engineering, North Carolina State Univ., Campus Box 7908, 431C Mann Hall, Raleigh, NC 27695, USA.

E-mail address: mpourghaz@ncsu.edu (M. Pour-Ghaz).

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(2012) [8] quantified the effects of tortuosity on the rate of flow in saturated discrete cracks and found that water permeability increases with the square of crack width and increasing tortuosity decreases water permeability by a factor of 4–6. Bentz et al. (2013) [9] simulated the influence of transverse cracking on chloride penetration into saturated concrete. They concluded that a simple 2-D simulation that considers diffusion may provide a conservative estimate on the influence of cracking of the projected service life of the concrete structures.

An early study investigating the effects of distributed damage on mass transport in concrete was presented by Samaha and Hover (1992) [10]. In this study, distributed cracking was induced by loading a specimen to 75% of its compressive strength; their results showed that chloride mitigation, tested by the Rapid Chloride Permeability Test, increased by approximately 20%. Breysse et al. (1994) [11] found that water permeability increases in concrete with distributed cracking generated from tensile loading. Some examples of continued research in this area include the works of Gérard and Marchand (2000) [12], who developed a simulation model for distributed cracking in concrete, finding that the presence of fracture networks increases diffusivity of cement-based material by a factor of 2–10. Yang et al. (2006) [13] subjected concrete to freeze-thaw as well as compressive loading (up to 90% of the compressive strength), finding that distributed cracks resulting from both damage mechanisms increased the connectivity of the fracture network, resulting in a reduction in electrical resistivity and increased sorptivity of the materials. Torrijos et al. (2010) [14] experimentally investigated the effects of ASR and thermally-induced cracking on concrete sorptivity. Their findings showed that sorptivity generally increases proportional to thermal damage but deceases after a threshold value. Chunsheng et al. (2012) [15] used compressive loading to induce distributed damage in concrete; these authors quantified damage using ultrasonic pulse velocity and found that damage increases air permeability significantly, while sorptivity and electrical resistivity were more strongly correlated to the total open porosity than damage alone. Chunsheng et al. (2012) [16] continued previous work in Ref. [15] finding that many transport properties, such as sorptivity, air permeability, electrical resistivity, and effective porosity are significantly affected by crack density. M'Jahad et al. (2014) [17] found that gas breakthrough pressure was a reliable indicator of damage presence in concrete. Concrete with freeze-thaw damage was shown to increase the amount of absorbed water and chloride penetration depth in Wang and Ueda (2014) [18]. Most recently, Ghasemzadeh and Pour-Ghaz (2014) [1] investigated the effects of freeze-thaw damage in concrete on transport mechanisms by providing experimental measurements and analytical models describing the effects of damage. They concluded that measurement techniques that are not based on the same transport mechanism will show the effects of damage on mass transport differently. Ghasemzadeh and Pour-Ghaz (2014) [1] provided this argument mainly based on their analytical models and suggested that further experimental work is necessary to better understand how the observed effect of damage depends on the method of observation. A brief summary of previous research on the effects of discrete and distributed fractures is shown in Table 1. Note that, for brevity, only experimental works investigating the effect of damage on specific mass transport mechanisms are included in Table 1.

Four conclusions can be drawn from the above literature review and the summary provided in Table 1. (1) The effect of discrete cracking is better understood as compared to the effect of damage. (2) It is unclear as to which transport mechanism, and subsequently which measurement technique, is more sensitive to the presence of damage. (3) The majority of these studies have used only a few mass transport measurement methods and, to the knowledge of the authors, the effect of damage has not been interpreted in the light of transport mechanisms used in these measurement methods. For example, it has been shown that while cracking can increase water permeability several orders of magnitude [19], diffusivity is less affected by cracking [2–4,18], but the relationship of the data to the mechanisms of mass transport was not discussed. (4) The sensitivity of different methods to the presence of damage is not discussed in the previous works.

The present work aims to develop a better understanding of the effects of damage on mass transport in damaged cement-based materials by investigating the mechanisms of mass transport involved. In this work, damage was induced by freeze-thaw loading in mortar specimens. Active acoustic emission (AE) was used to quantify the degree of damage. Passive AE was also used to monitor damage formation during the freeze-thaw cycles. Electrical Impedance Spectroscopy (EIS) and four-electrode Wenner methods were used to measure the bulk and surface electrical resistivity, respectively. Rapid Chloride Permeability Test (RCPT), sorptivity, drying, air permeability, water permeability, and desorption isotherm measurements were also carried out. In the following sections, the materials and methods used are described. Then, the results are presented and discussed. Finally, the conclusions of this study are presented.

2. Materials and specimen preparation

2.1. Mixture proportioning and specimen preparation

The mortar mixture was made with Ordinary Type I Portland Cement (OPC) and had a water-to-cement ratio (w/c) of 0.42. The fine aggregate consisted of natural river sand with a fineness modulus of 2.65 and a maximum aggregate size of 2 mm. The fine aggregate mainly consisted of silica and had 0.90% saturated surface dry (SSD) moisture content. The cement, aggregate, and water reducer content in the mixture were 609 kg/m^3, 1466 kg/m^3, and 0.50 kg/m^3, respectively. The mortar mixture was prepared following ASTM C192 [20].

The mortar mixture was cast in 102 mm × 204 mm cylindrical molds. Mortar cylinders were kept sealed for the first 24 h and were then demolded and cut into appropriate geometries (for different experiments as discussed below in Table 2) using a diamond-tipped wet saw. Top and bottom ends of the cylindrical specimens (roughly 25 mm) were cut and discarded to minimize the possible end-effects. While cutting the specimens may result in microcracking close to the cut surfaces, this damage is significantly smaller than the damage due to freeze-thaw which was monitored as described later. All of the specimens were cured in lime-saturated water at 25 ± 1 °C for 18 months after cutting to achieve high degree of hydration, a uniform saturation, and a uniform initial condition.

2.2. Number of specimens used in each test

A large number of tests were performed in this work. A detailed description of each test is provided in the Methods Section. Table 2 reports the total number of specimens and the number of replicates used in each test. All tests included a set of reference specimens (with no damage) with the same number of replicates indicated in Table 2. The dimensions of the specimens used in each test are also reported. The size of the specimens for each test method was chosen based on the standard test method or previously published literature when applicable. It should be noted that the dedicated specimens were made for each test and specimens were not used in multiple tests. Furthermore, dedicated specimens were made for each degree of damage in each test, except for acoustic emission