SMYL, DANNY JAMES. Electrical Imaging and Numerical Simulation of Unsaturated Moisture Flow in Cement-Based Materials. (Under the direction of Mohammad Pour-Ghaz and Gregory Lucier.)

Deterioration of concrete structures generally occurs in the presence of moisture. Moisture is essential for the majority if the deterioration processes and also facilitates transport of aggressive agents that contribute to corrosion of reinforcing steel or degradation and transformation of hydration products. Due to environmental exposure, temperature and the degree of moisture saturation fluctuate throughout the service life of a structure.

The kinetics of moisture flow considering the coupling of variable saturation and distributed damage (cracking) are complex. This complexity has led to significant challenges in understanding moisture transport in unsaturated cement-based materials. It is therefore no surprise that material models, simulation methods, and visualization techniques are underdeveloped for damaged, unsaturated cement-based materials. Yet, such knowledge and modeling techniques are essential in service-life predictions and assessment of built structures.

This thesis aims to deepen fundamental understanding of unsaturated moisture flow in cement-based materials. In the first contribution, electrically-based methods are developed to visualize highly-transient moisture flow in damaged and undamaged material. The electrically-based methods are shown to substantially improve upon the small-size limitations of standard visualization techniques (X-ray, γ-ray, and neutron imaging). Moreover, the visualizations are shown to have adequate resolution to accurately depict variable saturation.

The second contribution of the thesis is the development of material models and numerical simulation techniques for moisture flow in cement-based materials with distributed damage. In this effort, two simulation methods are used: one that considers moisture flow by homogenizing transport properties of the unsaturated/damaged material under hysteresis and another that considers transient unsaturated flow between fracture and undamaged material phases (dual-permeability). The results show that both methods model unsaturated flow in damaged cement-based material well, however dual-permeability model better simulated flow at late stages of ingress.
Electrical Imaging and Numerical Simulation of Unsaturated Moisture Flow in Cement-Based Materials

by
Danny James Smyl

A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

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APPROVED BY:

_________________________  ___________________________
Michael Borden              Arvind Saibaba

_________________________  ___________________________
Mohammad Pour-Ghaz          Gregory Lucier
Co-chair of Advisory Committee Co-chair of Advisory Committee
DEDICATION

BIOGRAPHY

Danny was born in Edmonton, Alberta November 11, 1988. He immigrated to the Hays, Kansas at the age of three and obtained a high school diploma from Hays High School. Thereafter, he attended the University of Kansas, obtaining a BS in Civil Engineering in May, 2011. He received a commission as a second lieutenant in the United States Marine Corps (USMC) in September, 2011. In May, 2012, he obtained a MS in Civil Engineering under the direction of Professor David Darwin.

After graduation, Danny spent a short period as a concrete research engineer at the Materials and Research Division in the Kansas Department of Transportation. Danny then graduated from USMC Basic Officer School and Combat Engineering Officer Course. He then reported to 2d Combat Engineer Battalion, Camp Lejeune, NC where he was assigned as a Platoon Commander of a Heavy Equipment Platoon. The Platoon executed orders in OEF 14.1 and 14.2, stationed aboard Camp Leatherneck, Afghanistan. Danny also served in operational and administrative billets during his time at 2d CEB.

After completing active duty, Danny began PhD studies at NCSU and reported to 4th CEB in Baltimore, Maryland. He served as a company executive officer and assistant operations officer during his two year service in the USMCR. While at NCSU, Danny was primarily supervised by Dr. Mohammad-Pour-Ghaz, where he studied unsaturated moisture flow in porous materials, the use of electrical methods to visualize moisture flow, and the use of electrical methods to visualize damage in structures. Danny also worked closely with Dr. Gregory Lucier, where he completed a long-term NCDOT project investigating the effects of latex polymers on rapid-setting concrete overlays.

In his final year at NCSU, Danny received a Fulbright Grant to Finland. While in Finland, Danny was supervised by Dr. Aku Seppänen at the University of Eastern Finland, Kuopio, Finland. In their research, Danny and Aku developed an advanced electrically-based method for visualizing damage processes in large-scale structural members.
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Chapter 1

Introduction

1.1 General

The majority of deterioration processes in concrete structures occur in the presence of water. Water facilitates the movement of aggressive ions, which increases the corrosion rate of reinforcement. Freeze-thaw damage occurs due to the expansive nature of freezing water in the pores of cement paste. These, and more, deleterious mechanisms usually occur in unsaturated concrete with various levels of damage. Despite this, very little information regarding material models, simulation models, and visualization techniques for cement-based material are available. Such information is essential in the development of life-cycle modeling and the assessment of built concrete infrastructure.

In addressing these shortfalls, this thesis aims to develop a fundamental understanding of unsaturated moisture flow in cement-based materials. In doing this, imaging techniques are used to visualize three-dimensional flow in undamaged cement-based materials and materials with discrete cracks. In the second contribution, material modeling and simulation methods are developed for accurate prediction of flow considering moisture hysteresis and distributed damage.

1.2 Objectives

The following are the objectives of this work:

1. Develop qualitative and quantitative three-dimensional (3D) Electrical Resistance Tomography (ERT\textsuperscript{1}) schemes for visualizing unsaturated moisture flow in undamaged cement-based materials.

\textsuperscript{1}ERT is a special case of Electrical Impedance Tomography (EIT). Further details provided in Chapter 2.
2. Develop 3D ERT for visualizing moisture flow in cement-based materials with discrete cracks.

3. Develop a homogenized hydraulic material model and unsaturated moisture-flow simulation technique for damaged cement-based materials considering moisture hysteresis.

4. Develop a dual-phase hydraulic material model and unsaturated moisture-flow simulation technique considering transient flow between distributed fracture and undamaged material matrix.

1.3 Organization

This thesis is organized in seven chapters. Chapter 1 is the introduction and Chapters 2-6 are published articles in scientific peer-reviewed journals. The final chapter presents conclusions of the work.

In Chapter 2, a qualitative ERT scheme is used to for 3D imaging of unsaturated moisture ingress into undamaged cylindrical mortar specimens. Ingressing fluids of differing viscosity and surface tension are investigated. X-ray computed tomography (CT) and simulations of moisture flow are used as corroboration. This chapter in the present form is published in [191].

In Chapter 3, an ERT scheme is developed to quantitatively image 3D moisture flow in cement-based materials. The quantitative nature of the visualizations is accomplished using i) experimental measurements to relate hydraulic and electrical properties and ii) an absolute imaging scheme. The ERT reconstructions are corroborated with moisture flow simulations and X-ray CT. This chapter in the present form is published in [189].

In Chapter 4, the use of ERT to visualize unsaturated moisture flow in cement-based material with discrete cracks is investigated. This topic is first investigated using cylindrical mortar specimens with physically-simulated cracks of known geometry and moisture flow simulations. Secondly, moisture flow in specimens with loading-induced discrete cracks is visualized using ERT. This chapter in the present form is published in [192].

In Chapter 5, a homogenized moisture transport material model and numerical simulation technique is developed for unsaturated cement-based material with distributed damage. In this effort, a transport model with moisture retention hysteresis is considered. The results of the simulations are corroborated with experimentally-obtained sorption measurements. This chapter in the present form is published in [187].

In Chapter 6, a dual-phase (dual-permeability) moisture transport material model and simulation technique is developed for unsaturated cement-based material with distributed damage. In this model, moisture transport in undamaged material, distributed fractures, and be-
tween these phases is considered. The simulation results are corroborated with experimentally-obtained sorption measurements. This chapter in the present form is published in [188].

Chapter 7 is the final chapter, presenting conclusions of the thesis.
Chapter 2

Three-Dimensional Electrical Impedance Tomography to Monitor Unsaturated Moisture Ingress in Cement-Based Materials

2.1 Abstract

The development of tools to monitor unsaturated moisture flow in cement-based material is of great importance, as most degradation processes in cement-based materials take place in the presence of moisture. In this paper, the feasibility of Electrical Impedance Tomography (EIT) to monitor three-dimensional (3D) moisture flow in mortar containing fine aggregates is investigated. In the experiments, EIT measurements are collected during moisture ingress in mortar, using electrodes attached on the outer surface of specimens. For EIT, the so-called difference imaging scheme is adopted to reconstruct the change of the 3D electrical conductivity distribution within a specimen caused by the ingress of water into mortar. To study the ability of EIT to detect differences in the rate of ingress, the experiment is performed using plain water and with water containing a viscosity modifying agent yielding a slower flow rate. To corroborate EIT, X-ray Computed Tomography (CT) and simulations of unsaturated moisture flow are carried out. While X-ray CT shows contrast with respect to background only in highly-saturated regions, EIT shows the conductivity change also in the regions of low degree of saturation. The results of EIT compare well with simulations of unsaturated moisture flow. Moreover, the EIT reconstructions show a clear difference between the cases of water without and with the viscosity modifying agent, and demonstrate the ability of EIT to distinguish
between different flow rates.

2.2 Introduction

The mechanical, hydraulic, chemical, thermal, and electrical properties of porous media are significantly affected by the presence of moisture [49], [81], [19]. For this reason, non-destructive methods of monitoring and visualizing moisture movement and distribution in unsaturated porous media are of broad interest. A variety of non-destructive techniques to visualize moisture distribution in porous media have been developed. The majority of these methods are based on electromagnetic radiation, including X-ray absorption [81], [155], [170], [171], and [17], γ rays [48], [143], [140], neutron imaging [84], [230], [229], [96], [235], [46], [130], [126], [129], and nuclear magnetic resonance [131], [147], [81], [36], [78]. While electromagnetic radiation based methods generally provide high resolution images, these methods may be invasive, expensive, limited to testing small specimens, and/or have significant energy demand. On the other hand, electrically-based methods are generally inexpensive, non-invasive, and require comparatively lower energy [82], [127].

Electrical Impedance Tomography (EIT) is an electrically-based imaging modality in which the spatially distributed electrical conductivity of a target object is reconstructed from surface electrical measurements. In porous geo-materials, EIT has recently been used to image objects buried in underwater sediment [25] and to monitor unsaturated moisture flow in soil [42], [41], [40], [23] and sandstone [195]. In [79], three-dimensional (3D) EIT was compared with magneto-electric resistivity imaging, showing the feasibility of EIT in monitoring water and air movement in sand. Further studies included solute transport in heterogeneous material within a large-scale experimental tank in [186]. In geologic materials with low matrix permeability, research has included permafrost monitoring in crystalline rocks [103], conductive plume dilution in fractured rock environments [142], clay materials [105], and layered formations including clay rock [66]. 3D EIT imaging has also been extended to monitor moisture and ion movement in layered soils using a time-lapse automated EIT system by [104].

While the above works have shown the feasibility of EIT to visualize moisture flow and moisture distribution in geo-materials, 3D visualization of moisture flow using EIT in cement-based material has not been studied. Hydraulic and electrical properties of cement-based materials differ considerably from those of geo-materials, because of the significant differences in the microstructure of cement-based and that of geo-materials [201]. Cement-based materials generally have finer pore-size distribution and lower volumetric moisture content at saturation than many of the geo-materials tested in the previous EIT studies.

Portland cement-based materials are generally considered multiscale materials and their microstructure is often broken down into four levels. The smallest scale, commonly referred to
as Level 0, which is above the atomic scale, ranges from $10^{-10}$ to $10^{-9}$ m. The structure at this scale is made of calcium silicate hydrate solid (C-S-H solid) with a characteristic length of 5.6 nm and 18% porosity. At a level above the Level 0, Level I, encompassing length scales below $10^{-6}$ m, C-S-H solid and gel porosity form the so-called C-S-H phase with porosity ranging from 24 to 37% and characteristic length of 16.6 nm. Level II ranges from $10^{-6}$ to $10^{-4}$ m to and consists of C-S-H phase, unhydrated cement particles, calcium hydroxide crystals, aluminate phases, and capillary porosity. The volume of capillary porosity is dependent on the initial water-to-cement ratio (w/c) and the degree of hydration (extent of chemical reaction). In well-hydrated low w/c ratio system, generally below w/c = 0.42 in Portland cement-based materials, capillary porosity can be negligible, and in high w/c ratio systems with a low degree of hydration it can be a significant portion of the volume. For example at w/c = 0.60 with 50% degree of hydration, volume of capillary porosity is approximately 45% of the cement paste volume. Finally, Level III has a characterization length larger than $10^{-3}$ m. Level III describes mortar and concrete materials as composite materials consisting of cement paste, fine aggregate, coarse aggregate, and interfacial transition zone (ITZ). ITZ refers to the region in the immediate vicinity of the aggregate that can have properties different from that of bulk cement paste. We note there that the above description of microstructure follows the description by [49], [93], and [167].

The resolution of imaging modalities, specifically electromagnetic-based modalities, to capture microstructure features depends on many factors including the type of electromagnetic field, available energy, and the attenuation of the target. In X-ray computed tomography (CT), the resolution of the scanners range from very high resolution (synchrotron-based micro CT, 5-20 µm), intermediate resolution (medical scanners, 100 - 500 µm), to lower resolution scanners ($\approx 400$ µm) [221]. In application to cement-based materials, these modalities can be used to probe mainly Level II and III microstructure with grain sizes ranging from $10^{-6}$ to $10^{-3}$ m. X-ray radiography and tomography however are not a very powerful methods for monitoring moisture ingress in cement-based materials and can only provide information about the high moisture content regions in cement-based materials.

Neutron tomography commonly reports image resolutions of on the order of 50 µm [223], [214]. Recently, [84] used neutron radiography with 30 µm resolution. Therefore, neutron tomography can be used to probe Level II and III microstructure, similar to X-ray tomography. It should be noted, however, that neutron tomography is generally well-suited for moisture flow monitoring due to the high neutron cross-section of hydrogen. The ability of neutron tomography to capture moisture flow in geophysical applications was shown in [125]. Tomography and radiography using $\gamma$ radiation is less common than X-ray and neutron methods, with a resolution of $\approx 0.1$ mm [151], [52].

The resolution (or the so-called distinguishability in Isaacson’s sense [92]) of EIT is a function of many factors such as geometry and size of the target, prior information, mesh size,
current injection pattern, presence of noise, and measurement resolution. EIT, generally, has lower spatial resolution than electromagnetic radiation based tomographic methods due to the diffusive nature of electricity. EIT, however, has been shown to be a powerful modality in monitoring moisture flow in soil and cement paste [190], [84], [118].

Daily and coauthors [44], [28], and [29] were perhaps the first to study the feasibility of EIT to monitor moisture transport in cement-based materials. They used simple two- and four-point measurement schemes in 2D geometries. However, their results were not corroborated and their reconstructions provided low spatial resolution. Recently, EIT was used to monitor 1D moisture flow in concrete slabs [51]. The EIT reconstructions were compared against Ground Penetrating Radar (GPR) results. In a more recent work, [84] studied imaging of 2D moisture flow in cement paste containing no aggregates, and compared EIT reconstructions with Neutron Radiography images, showing a good agreement between the two imaging methods. These studies have shown the potential of EIT to be used as a non-destructive, non-invasive means of monitoring moisture flow in cement-based materials.

In the present work, we expand upon the previous work by [84] and attempt to answer the open research question at the end of their article: Can EIT be used to monitor 3D moisture flow in cement-based materials containing aggregates? To answer this question, we conduct an experimental study of imaging 3D moisture flow in cement-based mortar containing fine aggregates. To corroborate the EIT reconstructions, X-ray CT images and 3D simulations of unsaturated moisture flow are compared with the EIT reconstructions. We also investigate whether EIT has adequate sensitivity to detect the difference between flow rates of fluids with differing viscosity and surface tension (resulting from the addition of radiocontrast agent, Iohexol).

In the following sections of this paper, materials and sample preparation are presented, a brief review of the difference imaging scheme in EIT is provided, the EIT experimental measurement strategy is presented, the numerical method of simulating unsaturated moisture flow in cement-based material is discussed, and an overview of the X-ray CT imaging method used here is provided. Finally, in Results section, the EIT reconstructions corresponding to ingresses of water without and with the viscosity/surface tension modifying agent are illustrated, and compared with X-ray CT images as well as moisture transport simulations.

2.3 Materials and sample preparation

2.3.1 Fluids in the absorption test

In the experiments, two liquids were used: plain water and water with radiocontrast agent (Iohexol solution, diluted to 120 mg Iodine/ml). Iohexol was chosen as an additive to water because it is effective in improving the contrast in X-ray Computed Tomography images, which
was used as experimental corroboration with EIT in this work. It should be noted that trial experiments using plain water were performed, and water ingress was not observable with CT. Iohexol increases fluid surface tension and viscosity when added to water (Iohexol has surface tension and viscosity of 86.6 dyne/cm and of $2.3 \times 10^{-3}$ Pa·s at 25°C, while values of water are 71.9 dyne/cm and $8.9 \times 10^{-4}$ Pa·s at 25°C). In cement-based materials, increasing both the surface tension ($\gamma$) and viscosity ($\mu$) has been shown to change the rate of absorption proportional to $\sqrt{\gamma/\mu}$ ([194]). Therefore, water containing Iohexol was expected to penetrate the mortar specimen at a different rate than plain water. To confirm this, a sorption experiment was conducted.

### 2.3.2 Preparation of EIT and sorption test specimens

![Figure 2.1: (a) Prepared EIT specimen with PVC water reservoir, (b) mortar specimen and locations of the painted-silver electrodes](image)

The specimens in the EIT and CT experiments were made of mortar, consisting of cement paste and fine aggregates. Ordinary Portland cement (OPC, Type I) and fine aggregate consisting of non-angular siliceous natural river sand with a fineness modulus of 2.63 and maximum aggregate size of 2 mm were used. A high w/c ratio and low volumetric aggregate content ($v_a = 40\%$) were used to increase material porosity and permeability to accelerate the rate of moisture ingress and reduce the X-ray CT testing duration. The porosity of the cement paste,
Table 2.1: Material and hydraulic parameters

<table>
<thead>
<tr>
<th>w/c</th>
<th>v _a [\text{mm}^3]</th>
<th>\phi_p [\text{mm}^3]</th>
<th>K_s [\text{mm}^3]</th>
<th>\theta_s [\text{mm}^3]</th>
<th>\theta_i [\text{mm}^3]</th>
<th>\theta_r [\text{mm}^3]</th>
<th>I(\text{--})</th>
<th>\alpha [\text{1/mm}]</th>
<th>n(\text{--})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60</td>
<td>0.40</td>
<td>0.25</td>
<td>0.005</td>
<td>0.15</td>
<td>0.07</td>
<td>0</td>
<td>-9.0</td>
<td>0.026</td>
<td>1.77</td>
</tr>
</tbody>
</table>

\( \phi_p \), may then be estimated using \( \phi_p = \frac{\theta_s}{1 - v_a} \), where \( \theta_s \) is open porosity further discussed in Section 2.4.2. The mixing was carried out according to ASTM C192-06 [9] and two cylinders with diameter 10.20 cm and height 20.30 cm were cast. The cylinders were demolded after 18 hours and cut in half horizontally using a wet-saw to create the specimens used in EIT and CT testing.

Since the specimens were saturated after demolding at 18 hours, they were moved to an oven at 50°C for 5 hours to reduce their moisture content. The specimens were then sealed in two layers of plastic bags and placed inside an environmental chamber at 23°C for 21 days. This conditioning process was carried out to achieve a relatively uniform moisture content throughout the specimen. It should be noted that uniform moisture content is not necessary for EIT. The above conditioning resulted in an initial volumetric moisture content, \( \theta_i = 0.07 \), which was determined experimentally by completely drying a set of identically conditioned specimens of the same material and geometry. A summary of material properties are provided in Table 2.1.

For the sorption experiments that were used for studying the effect of Iohexol on the absorption rate of water, two cylinders with diameter and height of 5.0 cm were cast. The material was the same and the sample preparation procedure was similar to the specimens used in EIT and CT testing. However, unlike the EIT/CT specimens, the sorption test specimens were cast in PVC pipes and oven dried at 50°C for 24 hours after the 21 days of initial curing. Complete desaturation was selected as the initial condition to minimize moisture gradient in the specimen and to maximize the amount of absorbed fluid. It should be noted that since the only purpose of the sorption experiment was to verify that the addition of Iohexol reduces the rate of absorption, the initial condition was not a critical parameter. Sorption tests were carried out for 22 hours.

2.3.3 Preparation of electrodes and water reservoir

The electrodes used in EIT measurements were made of colloidal silver paint. The silver paint had a viscosity of 10 Pa \cdot s, a pH between 10.0 - 10.5, and a dried electrical resistivity of \( 1.60 \cdot 10^{-8} \text{\Omega} \cdot \text{m} \) [133]. This paint has a low resistivity and is fast drying, making it a suitable material for "painted" electrodes [153]. It has been shown in [153], [157], [164], [220], [61] that the use of fast-drying colloidal silver paint reduces contact impedance compared to conventional
electrodes (i.e. copper foil or metallic sheets). Since the silver paint dries rapidly (on the order of a few seconds), the penetration into the immediate pore system is negligible. Especially, in this work, the dimensions of specimens are orders of magnitude larger than the potential penetration depth of the paint, reducing the potential influences on the measurements. In addition, this work employs the difference imaging scheme where the effect of electrode contact impedance is largely subtracted between the two sets of measurements.

A total of 24 square shaped electrodes (with dimension of 1.3 cm × 1.3 cm) were painted on the side surface of the cylindrical specimens using a small brush. The electrodes were arranged in three equally spaced 8-electrode rings. Figure 2.1b shows the specimen and the locations of the electrodes. After the silver paint electrodes had dried, an 18-gage wire was attached to each electrode using an electric tape, and its contact was secured using a zip tie.

The slight variations in electrode sizes and shapes, in principal, introduces measurement and modeling errors. In addition, there are multiple contacts in this experimental setup, namely, sliver paint/sample and wire/silver paint electric contacts that can affect the results. The contact impedance of the silver paint/sample is the most important contact impedance that needs to be properly accounted for in modeling (the copper wire to silver electrode contact impedance is very small since both materials are very conductive). Once more, since difference imaging is used, much of the systematic experimental and modeling errors cancel. It should also be noted that the length of the wires can also affect the measurements. In this work the length of wires was cut to the minimum length required to reach the specimen from the EIT equipment. In addition, the frequency of the measurements is relatively low and the measurements are not significantly impacted by the length of the wires.

To facilitate absorption, a water reservoir made of PVC was mounted on the top surface of each specimen using silicon caulking. The silicon caulking was fast-drying and had a very high viscosity (as compared to water), which minimized its penetration into the specimen. Moreover, it can be seen in the X-ray CT images (Section 3.7), where the silicon showed significant contrast to the mortar, there was minimal penetration into the specimen. The length and internal diameter of the PVC pipe was 5.0 cm and 0.95 cm, respectively, and it was positioned eccentrically 1.3 cm off-center. After placing the water reservoirs, the mortar cylinders were wrapped with transparent tape to prevent evaporation of water from the specimens’ surface during the experiment (Fig. 2.1a). To minimize evaporation from sample during the test, the exterior of the specimen and around the base of the water reservoir was sealed with two layers of transparent plastic tape.
2.4 Methods

In the experiments, water without and with the radiocontrast agent was let to ingress each mortar specimen from a water reservoir (See Section 2.3.3 and Fig. 2.1a). EIT measurements and CT scanning were both carried out at several time intervals during the absorption of moisture. The EIT and CT measurements were also collected prior to the addition of the solution to the reservoir ("reference measurement," see below). The experimental results were corroborated with a numerical simulation of unsaturated moisture flow. The methods used in the study are described in this section.

2.4.1 Electrical impedance tomography

Imaging Scheme

In EIT, a series of electric currents are injected between pairs of electrodes at the surface of a target and corresponding to each current injection, the electrical potential differences (voltages) between multiple electrode pairs are measured. In general, the same set of boundary electrodes is used for current injections and potential measurements. Based on these measurements, the spatial distribution of the electrical conductivity inside the object is reconstructed. Mathematically, the reconstruction problem in EIT is a non-linear ill-posed inverse problem, in the sense that its classical solutions are non-unique and very sensitive to modeling errors and measurement noise.

A variety of computational methods for image reconstruction in EIT have been developed [22]. In a broad sense, the reconstruction methods can be categorized as absolute and difference imaging. In absolute imaging, the distribution of electrical conductivity is reconstructed based on a single set of potential measurements during which the object is assumed to be non-varying. Absolute imaging often necessitates iterative solution of the nonlinear EIT problem. In difference imaging, the change in the conductivity between two states is reconstructed from potential measurement data corresponding to these two states. In this paper, the conductivity changes in a specimen at different stages of moisture ingress are reconstructed using difference imaging.

The inverse problem of EIT requires a forward model. The most accurate known forward model for the EIT measurements is the Complete Electrode Model [37], [193]. The CEM consists of the partial differential equation

\[ \nabla \cdot (\sigma \nabla u) = 0, \quad x \in \Omega \] (2.1)

and the boundary conditions

\[ u + \xi_\ell \sigma \frac{du}{dn} = U_\ell, \quad x \in e_\ell, \quad \ell = 1, \ldots, L \] (2.2)
\[ \sigma \frac{du}{dn} = 0, \quad x \in \partial \Omega \setminus \bigcup_{\ell=1}^{L} e_\ell \quad (2.3) \]

\[ \int_{e_\ell} \sigma \frac{du}{dn} dS = I_\ell, \quad \ell = 1, \ldots, L \quad (2.4) \]

where \( \Omega \) is the target volume, \( \partial \Omega \) is its boundary, \( \sigma \) is the electrical conductivity, \( u \) is the electric potential, \( n \) is the unit normal, \( e_\ell \) is the \( \ell \)th electrode, and \( \xi_\ell, U_\ell \) and \( I_\ell \), respectively, are the contact impedance, electric potential and total injected current corresponding to \( e_\ell \). Moreover, the current conservation law must be fulfilled

\[ \sum_{\ell=1}^{L} I_\ell = 0 \quad (2.5) \]

and the potential reference level must be fixed

\[ \sum_{\ell=1}^{L} U_\ell = 0. \quad (2.6) \]

To approximate the solution of the CEM for an object with arbitrary geometry, a numerical method is necessary. In this work, Finite Element Method (FEM) is employed [206]. The FEM approximation of the forward model used in this work follows the well-known implementation of the variational equation [210]. The meshing of the domain is detailed later in this section.

In difference imaging, the change in electrical conductivity \( \delta \sigma \) from a reference conductivity state \( \sigma_o \) to the current state of conductivity, \( \sigma \), is reconstructed (i.e., \( \delta \sigma = \sigma - \sigma_o \)). A global linearization approach using a Taylor Polynomial at \( \sigma_o \) is used such that

\[ U(\sigma) = U(\sigma_o) + J[\sigma - \sigma_o] + O(||\sigma - \sigma_o||^2) \quad (2.7) \]

where \( U(\sigma) \) is the finite element approximation of the mapping between the discretized conductivity \( \sigma \) and a vector consisting of electrode potentials, \( J = \frac{dU}{d\sigma}(\sigma_o) \) is the Jacobian matrix at \( \sigma_o \), and \( O(||\sigma - \sigma_o||^2) \) denotes the higher-order terms. When the higher-order terms are neglected and the observation noise accounted for, the observation model for \( \delta V = V - V_o \), the difference between measurement realizations \( V \) and \( V_o \) corresponding to states \( \sigma \) and \( \sigma_o \), can be written as

\[ \delta V \approx J\delta \sigma + \bar{v} \quad (2.8) \]

where \( \delta \sigma = \sigma - \sigma_o \) is the change in the conductivity, and \( \bar{v} \) is the difference between randomly-distributed observation noises in the two sets of measurements.

In Eq. (2.8), the measured potential difference between the two states, \( \delta V \), is linearly related
to the conductivity change, $\delta \sigma$, using a global linearization at an estimated reference state $\sigma_o$. This has a few consequences: (i) since the potential difference between two states is considered, some of the modeling errors and/or systematic measurements errors that exist in both measurement sets may cancel out. This makes difference imaging a rather tolerant imaging scheme to systematic modeling or measurements errors. (ii) Since the nonlinear problem is globally linearized, the solution does not require iterations, and the computational cost of the reconstruction decreases. (iii) Due to the global linearization, the computed changes in conductivity do not necessarily reflect the actual conductivity changes. This is especially true if the changes in conductivity are large. This makes the results of difference imaging qualitative [209]. (iv) Difference imaging may fail to provide reasonable solution if the change in conductivity with respect to reference state is very large [83]. (v) If the linearization point, $\sigma_0$, is far from the actual conductivity of the reference state, results may be unreasonable. In general, difference imaging is a powerful tool when the primary interest is to observe the location and approximate change in electrical conductivity.

Due to the ill-posed nature of the EIT inverse problem, solving the conductivity change $\delta \sigma$ from Eq. (2.8) in the least squares sense would yield non-unique and unstable solutions [207]. Therefore, regularization is needed. In generalized Tikhonov regularization [200], the solution of the (linearized) inverse problem is written in the following form

$$\hat{\delta \sigma} = \arg \min_{\delta \sigma} \left\{ ||\delta V - J \delta \sigma||^2 + p_{\delta \sigma}(\delta \sigma) \right\}$$

(2.9)

where $p_{\delta \sigma}(\delta \sigma)$ is a side constraint term which regularizes the solution ([86], [20]). In this paper, $p_{\delta \sigma}(\delta \sigma)$ is chosen to be of the form $p_{\delta \sigma}(\delta \sigma) = \alpha ||L_{\delta \sigma} \delta \sigma||^2$, where $L$ is a first order discrete differential operator and $\alpha$ is a regularization parameter which controls the weight of the side constraint in the solution. Such a choice of $p_{\delta \sigma}(\delta \sigma)$ is known to promote spatial smoothness in the solutions; smoothness promoting regularization is particularly well-suited for diffusive processes, such as moisture ingress [113], and was used also by Hallaji et al (2015). For alternative choices of $p_{\delta \sigma}(\delta \sigma)$, see e.g. [95].

In this work, MATLAB implementation of [2], [152] was used. A total of 828,188 quadratic 10-node tetrahedral elements with a maximum element dimension of 2.0 mm were used in discretization of the domain. The mesh (shown in Figure 2.2) was generated using Delauney meshing and application of NetGen [182]. The meshing on and near the electrodes used the same meshing criteria as the elements within the modeled specimen. Further, the six nodes used on the electrode surface correspond to the nodes on the side of the same tetrahedral element within the specimen volume. The modeling of the electrodes approximated the contact impedance as 0.01. We would like to point out that due to the use of the difference imaging scheme, in general, the value of contact impedance does not affect the reconstructions since its
effect is subtracted between the two sets of measurements.

Figure 2.2: FEM mesh used in EIT reconstructions

EIT measurement strategy

The EIT measurements were carried out using an in-house developed EIT equipment described in [84]. In all measurements, an alternating current with 0.10 mA amplitude and 40 kHz frequency was used. This frequency was chosen based on Electrical Impedance Spectroscopy (EIS) measurements; at frequency 40 kHz, the imaginary component of the impedance was at the minimum. The accuracy of the potential measurements was $\pm 1 \times 10^{-8}$ V. The current injection pattern consisted of: (i) injecting current between electrode pairs $(i,j)$ on the same ring of electrodes $i = 1 \ldots 8, 9 \ldots 16, 17 \ldots 24$ and $i, j = 1 \ldots 8, 9 \ldots 16, 17 \ldots 24$ and $i \neq j$, (ii) between electrode pairs $(k,l)$ located on different rings of electrodes $k = 1, l = 9 \ldots 16$ and $k = 8, l = 17 \ldots 24$, and $k = 1, l = 17 \ldots 24$. Corresponding to each current injection, potential measurements were taken with respect to a common ground. Electric potential differences were only considered between adjacent electrodes on the same ring level. This current injection and potential measurement protocol resulted in 561 current injections and 4488 potential measurements for each set of EIT measurements. The sampling frequency was automated in the EIT equipment, which was a function of the excitation frequency.
2.4.2 Numerical simulation of unsaturated moisture transport

General

The isothermal unsaturated moisture transport in porous media was simulated using Richards’ Equation [166]:

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left( K(h) \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K(h) \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K(h) \frac{\partial h}{\partial z} + 1 \right)
\]  
(2.10)

where \( K = K(h) \) (mm/hr) is the unsaturated hydraulic conductivity, \( \theta \) (mm³/mm³) is the volumetric moisture content, \( h \) (mm) is the pressure head, \( x, y, \) and \( z \) are the spatial coordinates [197, 155]. In classical Richards’ Equation, air diffusion and dissolution are neglected. In this work, a finite element approximation of Eq. (4.10) was used to simulate moisture flow in mortar.

Material model

In general, the unsaturated hydraulic conductivity is expressed as the product of the relative hydraulic conductivity \( K_r \), and the saturated hydraulic conductivity \( K_s \), \( K = K_r K_s \). For unsaturated porous media, Mualem’s equation [135] is used to describe \( K_r \)

\[
K_r = \Theta I \left[ \int_0^\Theta \frac{1}{\frac{1}{h(x)}}, dx \right]^2 \left[ \int_0^1 \frac{1}{\frac{1}{h(x)}}, dx \right] \]  
(2.11)

\[
\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r}
\]  
(2.12)

where \( 0 \leq \Theta \leq 1.0 \) is the effective material saturation, and \( \theta_r \) is the residual moisture content; \( \theta_r = 0 \) is generally considered as an appropriate assumption for cement-based materials [156], [155]. Moreover, \( \theta_s \) is the saturated water content that was determined experimentally in this work), \( I \) is the tortuosity and pore connectivity parameter and in this work \( I \) was taken from [187]. Further discussion of \( I \) in cement-based materials is provided in [13] and [160]. In this work, \( K_s \) was determined experimentally using Darcy’s Law and the procedure in [70].

In order to calculate the integrals in Eq. 6.4, the effective material saturation was expressed as a function of the pressure head, \( \Theta = \Theta(h) \) using the van Genuchten model ([203], [204]):

\[
\Theta = \frac{1}{\left[ 1 + (\alpha h)^n \right]^m}, \quad m = 1 - \frac{1}{n}
\]  
(2.13)

where \( \alpha \) (mm⁻¹) and \( n \) (−) are fitting parameters. For cement-based materials, instead of expressing water retention as \( \Theta = \Theta(h) \), the material sorption isotherm is generally obtained experimentally as \( \Theta = \Theta(RH) \), where \( RH \) denotes relative humidity. In this work, the desorption isotherm was experimentally determined using an automated sorption analyzer [211], [156].
It should be noted that in the present work we neglected the hysteresis effect for simplicity. To convert the experimentally obtained isotherm $\Theta(RH)$ to the moisture retention curve as $\Theta(h)$, the Kelvin-Laplace Equation was used [155], [108]:

$$h = \frac{\rho_w RT}{m_w} \ln(RH)$$  \hspace{1cm} (2.14)

where $\rho_w$ (g/mm$^3$) is the density of water, $R$ (8.314 J K$^{-1}$ mol$^{-1}$) is the universal gas constant, and $m_w$ (g/mol) is the molecular weight of water. By fitting the model in Eq. (4.13) to the water retention curve $\Theta(h)$, van Genuchten parameters $\alpha$ and $n$ were obtained. A summary of the hydraulic properties are provided in Table 2.1. Figure 4.4 shows the fitted van Genuchten model and experimentally obtained data points.

Figure 2.3: Fitted moisture retention curve for mortar using van Genuchten parameters

Simulation of moisture flow

The moisture flow in the specimen was simulated using a commercially available Finite Element Software HYDRUS 3D [215]. The finite element scheme was solved using the Galerkin formulation of Richards Equation with linear basis functions. Zero-flux boundary conditions were considered at all surfaces except for the surface from which water penetrated (area under the water reservoir), which was modeled as a 9.5 mm diameter circle saturated throughout the
simulation. Uniform initial moisture content, $\theta_i = 0.07$ was considered as discussed in Section 2.3. The finite element mesh consisted of linear tetrahedral elements with four nodes and a maximum dimension of 4 mm, a total of 124,138 elements were used in the simulation. The finite element model was solved in terms of moisture content and the preconditioned conjugate-gradient method was used to solve the resulting systems of equations. The mesh, with the same dimensions of the EIT specimen is shown in Figure 2.4.

![Figure 2.4: FEM mesh used in moisture flow simulations](image)

### 2.4.3 X-ray CT imaging

To corroborate EIT reconstructions, X-ray Computed Tomography (CT) imaging was conducted using a full-scale medical CT scanner with a peak beam energy of 120 kV and intensity of 40-200 mA (see Fig. 3.3). In the CT scanner, the X-ray tube rotates perpendicular to the circular cross-section of the specimen. As the fan beam rotates around the specimen, detectors on the opposite side are activated and measurements are taken. Upon completing a full rotation, the X-ray absorption coefficient, $\mu$(mm$^{-1}$), is computed in voxels within the measured slice. X-ray radiation transmitted through the specimen is related to $\mu$ via the Lambert-Beer law:

$$I_x = I_0 \exp (- \int \mu d\ell)$$  \hspace{1cm} (2.15)

where $I_x$ is the intensity of the transmitted X-ray passing through the specimen, $I_0$ is the
incident X-ray intensity, and $d$(mm) is the specimen thickness which is computed during the reference CT scan. The voxel values of the CT images, $\mu - \mu_{\text{water}}$, were normalized by $\mu_{\text{water}} - \mu_{\text{air}}$ to get Hounsfield numbers $H$ is defined by [57]:

$$H = 1000 \times \frac{\mu - \mu_{\text{water}}}{\mu_{\text{water}} - \mu_{\text{air}}}.$$  \hfill (2.16)

Further, the spatial distribution of volumetric moisture content, $\theta$, was computed from the Hounsfield numbers ([199]):

$$\theta = \frac{H_s - H}{1000}. \hfill (2.17)$$

where $H_s$ is the Hounsfield value of a saturated material. Here, the value of $H_s$ was taken from $H$ values corresponding to voxels directly below the water reservoir, where the material was assumed to be completely saturated.

The specimen was scanned at time intervals of 30 minutes, 1, 2, 7 and 22 hours. Since testing was conducted medical facility, access of to the scanner was limited to normal business hours. Therefore, testing was conducted continuously for 7 hours and then once again during normal business hours the following day. 2D slices were taken through the horizontal and vertical cross sections in 0.6 mm slices. CT images were analyzed using digital imaging software [1]. We would like to note that the silver electrodes diffracted X-rays during the scanning, however the diffraction was minimal and did not impact the image analysis.

2.5 Results and discussion

Figure 2.6 shows the results of the experiment, where water with radiocontrast agent (Iohexol) was absorbed to a specimen. The left column of the figure shows 2D slices of the 3D EIT reconstructions corresponding to 30 minutes, 1, 2, 7, and 22 hours of moisture ingress, and on the right column, the respective CT images are depicted. The planes of the vertical 2D slices pass through the center of the water reservoir, extending to the sides of the specimen. The rectangles in the EIT images illustrate the locations of electrodes. It should be noted that the EIT images represent the change in the electrical conductivity, $\delta\sigma$ (mS/cm), because the difference imaging scheme was used, as discussed in Section 4.4.1, while the CT images show the volumetric moisture content, $\theta$, computed using the procedure in Section 3.5. The relationship between volumetric moisture content, $\theta$, and electrical conductivity, $\sigma$, is highly nonlinear for cement-based materials. Therefore, the comparison between the left and right column in Figure 2.6.

\footnote{X-Ray CT images show the water reservoir at the center of the specimen due to the orientation of the sample during testing (shown in Fig. 3.3).}
Figure 2.5: Full-scale medical CT scanner with a peak beam energy of 120 kV and intensity of 40-200 mA testing the EIT specimen used in this study.
2.6 is only qualitative.

X-ray CT images and EIT reconstructions do not compare well: The CT shows the change of the moisture content, $\theta$, only in a small area below the water reservoir, while EIT images imply deeper penetration of moisture. Indeed, after 22 hours of moisture ingress, the conductivity distribution has changed in a volume extending to more than half of the specimen height. Moreover, the EIT images show more distinct variability in $\delta\sigma$ than CT shows in $\theta$. These qualitative differences between CT and EIT images are results of CT being capable of showing only high degrees of saturation. This conclusion is in agreement with the previous study by [155] in which X-ray radiography could only detect areas with moisture content close to saturation and the gradient of moisture content was not observable in a small square sample with dimensions $25.4 \text{ mm} \times 25.4 \text{ mm}$ and $6.35 \text{ mm}$ thick. Observing the gradient of moisture content in cement-based samples using X-ray radiography and X-ray CT is even more difficult in larger samples [170], [171]. The result of this experiment demonstrates that EIT has potential for (at least qualitatively) imaging the unsaturated moisture flow in large dimensional objects made of cement-based material – in conditions where standard medical X-ray CT scanners fail.

Since CT images did not capture low levels of moisture content, simulation of unsaturated moisture flow was selected as an additional corroboration method for EIT results. Figure 2.7 shows 2D slices of 3D EIT reconstructions of water penetration without Iohexol (left column) and 2D slices of 3D numerical simulations of unsaturated moisture flow (right column). This comparison of simulation results reporting quantitative volumetric moisture content, $\theta$, to EIT reconstructions of $\delta\sigma$ is again qualitative due to the difference imaging approach. Nevertheless, the spatial distributions of $\delta\sigma$ and $\theta$ compare well at times from 30 minutes to 7 hours. The EIT reconstruction corresponding to 22 hours of moisture penetration shows large artifacts, which is discussed later in this section.

We would like to add that a comparatively lower number of elements were used in moisture flow simulations as compared with EIT reconstructions (elements used in moisture simulations are approximately twice the maximum dimension of than those used in EIT). However, since the size of the elements in moisture simulations are already very small, further decrease of the element size would only minimally impact the moisture simulation results. It should be noted that since herein we only qualitatively compare the results of EIT with moisture flow simulations the difference in mesh size between EIT and moisture flow simulations does not impact the overall conclusions and findings of the work.

Figure 2.8 compares the EIT reconstructions from the two experiments: ingress of plain water (left column) and ingress of water with Iohexol (right column). The EIT images show a clear difference in the absorption rates of plain water and water with Iohexol. The size of the wetted volume is consistently larger in the images corresponding to ingress of plain water. Moreover, the values of the conductivity change $\delta\sigma$ are significantly higher in the left column.
Figure 2.6: Two-dimensional (2D) slices of the conductivity change based on 3D EIT reconstructions (left column), and CT images (right column) at different times of the moisture ingress (with radiocontrast agent, Iohexol).
Figure 2.7: Two-dimensional (2D) slices of the conductivity change based on 3D EIT reconstructions (left column), and unsaturated moisture flow simulations (right column) at different times of the moisture ingress.)
of Figure 2.8 than in the respective images in the right column, suggesting significantly higher moisture content – and absorption rate – for plain water. In analyzing the raw measurement data, it was apparent that potential differences decrease with the ingress of moisture in the case of both Iohexol and plain water. However, due to the ill-posed nature of the EIT reconstruction problem, it is very difficult to draw quantitative conclusions from the raw data (small changes in potential measurements can correspond to very large differences in reconstructions due to the ill-posedness of the EIT inverse problem).

We would like to highlight that different scale bars are used in illustration of EIT reconstructions of specimens with Iohexol and plain water ingress. The different scales allow illustration of the regions of the moisture penetration in samples with Iohexol since they have approximately three time smaller conductivity change. We also would like to mention that the values of conductivity change in difference imaging scheme are qualitative due to the reasons discussed in Section 4.4.1. This means that the estimated change in conductivities do not necessary represent the actual conductivity change, rather a "larger change" in conductivity.

The results presented here indicate that EIT has enough spatial resolution to enable visualization of moisture and differentiate the flow rate of different fluids. Whereas X-ray CT could not be used to detect moisture movement, especially at low levels of saturation due to low contrast between the regions of varying moisture content at low moisture content levels. It should be noted that while EIT had sufficient resolution to image areas of low moisture content, X-ray CT could detect features that EIT could not. For example, in Figure 2.6 X-ray CT detected the large pores within the specimen due to contrast between the air and surrounding material. Such small features are generally difficult to detect with EIT, especially with difference imaging, since the scheme subtracts features present in the reference measurements. In principal, small features such as air voids, can be detected with absolute imaging provided they are within distinguishability limit and proper prior information is used.

The sorptivity test described in Section 2.3 resulted initial sorptivities of $0.38 \text{ (mm/} \sqrt{\text{hr)}}$ for plain water and $0.31 \text{ (mm/} \sqrt{\text{hr)}}$ for water with Iohexol, respectively, indicating an 18% decrease of the absorption rate with the addition of Iohexol to water. The result of the sorptivity test thus supports results of the EIT experiment. Therefore, although the difference reconstructions in EIT are often qualitative, they enable distinguishing between different rates of moisture flow in this experiment.

To better visualize the ability of EIT to image moisture flows in 3D, the reconstructions from the two sets of experiments are illustrated in the 3D images shown in Figure 4.7. Again, the images indicate higher absorption for plain water than for water with Iohexol. Both of the 22-hour reconstructions show artifacts discussed above. However, in the reconstruction corresponding to ingress of water with Iohexol, there are less artifacts.

The significant artifacts observed in the EIT reconstruction of plain water ingress after
Figure 2.8: Two-dimensional (2D) slices of the conductivity change based on 3D EIT reconstructions for water (left column), and two-dimensional (2D) slices of the conductivity change based on 3D EIT reconstructions for water with Iohexol (right column).
Figure 2.9: 3D EIT reconstructions of conductivity change for water (left column), and 3D EIT reconstructions of conductivity change for water with Iohexol (right column).
22-hours may have resulted from the change in contact impedance. The contact impedance between the silver paint and the specimen can change due to moisture reaching to the electrode. Moreover, in difference imaging, the inaccuracies in estimating contact impedance, in general, cancel out in between the two measurement sets if the contact impedance remains the same. In this case, the presence of moisture changes the contact impedance and therefore their effect does not cancel out between the measurements. Another reason for these artifacts is the significant conductivity change from the reference state. In the difference imaging, global linearization is used with the implicit assumption that the conductivity change with respect to the reference state is small (see Section 3.1). Therefore, when conductivity change is very large and encompasses a large portion of the domain, the assumptions of difference imaging are violated, resulting in the artifacts seen in late-stage ingress. In addition, while efforts were made to avoid drying of the sample during the experiments, some drying of the bottom of the specimen may have occurred during experimentation, resulting in a drop of conductivity.

2.6 Summary and Conclusions

In the present paper, we investigated (i) whether EIT can be used to monitor 3D moisture flow in cement-based materials containing aggregates, and (ii) whether EIT has adequate sensitivity to detect difference in the flow rate of fluids of differing viscosity and surface tension. We conducted an experimental study, where 3D moisture flow in cement-based mortar containing fine aggregates was imaged using EIT and X-ray Computed Tomography (CT). In EIT, the difference imaging scheme was selected to reconstruct the change of the electrical conductivity of mortar from a reference state, i.e., the state before the moisture ingress. Measurements were performed during the ingress of water without and with Iohexol, a radiocontrast agent that increased viscosity and surface tension. In the presence of Iohexol, the rate of moisture penetration was slower, which was confirmed by performing a sorption test.

CT images were compared to EIT results; however, CT images showed only the highly-saturated region directly below the water reservoir. To facilitate the comparison of flow patterns including low levels of saturation, numerical simulation of moisture flow was chosen as an additional corroboration method. The qualitative comparison of the EIT reconstructions with the results of numerical simulation of unsaturated moisture flow shows that the EIT reconstructions agree with the results of simulations at early stages of moisture ingress. Moreover, the results show that EIT provides sufficient sensitivity to show differing flow rates of fluids with differing viscosity and surface tension. At later stages, significant artifacts appear in the reconstructions. Therefore, at later stages of moisture ingress, where the change in electrical conductivity may be larger, different imaging schemes in EIT may be needed. In conclusion, difference-imaging based EIT can provide a suitable non-destructive, non-invasive method of
monitoring unsaturated 3D moisture flow in cement-based material at least at early stages of moisture ingress in cement-based materials containing aggregates.
Chapter 3

Quantitative Electrical Imaging of Three-Dimensional Moisture Flow in Cement-Based Materials

3.1 Abstract
The presence of moisture significantly affects the mechanical, hydraulic, chemical, electrical, and thermal properties of cement-based and other porous materials, and therefore, methods for detecting and quantifying the moisture ingress in these materials are needed. Recent research studies have shown that the ingress of moisture in porous materials can be qualitatively imaged with Electrical Impedance Tomography (EIT) – an imaging modality which uses electrical measurements from object’s surface to reconstruct the electrical conductivity distribution inside the object. The aim of this study is to investigate whether EIT could image the three-dimensional volumetric moisture content within cement-based materials quantitatively. For this aim, we apply the so-called absolute imaging scheme to the EIT image reconstruction, and use an experimentally developed model for converting the electrical conductivity distribution to volumetric moisture content. The results of the experimental studies support the feasibility of EIT for quantitative imaging of three-dimensional moisture flows in cement-based materials.

3.2 Introduction
The mechanical, hydraulic, chemical, thermal, and electrical properties of porous media are significantly affected by the moisture content within the media [49, 80, 19], and especially in cement-based materials, the majority of deterioration processes take place in the presence of moisture [34, 112, 43]. For these reasons, there has been a significant interest in develop-
ing methods of monitoring moisture flows in cement-based materials and other porous media. While some high-resolution imaging methods of monitoring moisture flow in porous media are available, e.g. X-ray imaging [155, 154, 170, 171], γ-rays [48, 143, 140], neutron imaging [111, 84, 230, 229, 96, 235, 46, 130, 126, 129], and nuclear magnetic resonance [131, 147, 81, 36, 78], these methods are often expensive, limited to testing small specimens, and/or have significant energy demand. Electrically-based methods, on the other hand, have often a limited spatial resolution but are generally inexpensive, non-invasive, and require comparatively lower energy [82, 127, 115, 225, 76, 77, 75]. One electrically-based method that has been recently shown to be particularly promising for monitoring moisture in porous media is Electrical Impedance Tomography (EIT) [191, 84, 51].

In EIT, the electrical conductivity distribution inside an object is reconstructed based on voltage measurements from the surface of the object. Previous studies have demonstrated the feasibility of EIT to qualitatively image unsaturated moisture flows in porous media. Such research includes: 1D and 2D unsaturated moisture flow in soil [42, 41, 40, 23] and cement-based material [44, 29, 51, 84], as well as 3D moisture flow in sand [79], sandstone [195], soil [104] and cement-based materials [191]. In all these works, (the spatial map of) the increase of the moisture content with respect to some initial state was inferred qualitatively from a relative increase in the electrical conductivity (or decrease in the electrical resistivity) distribution. The change in the electrical conductivity was estimated using a linear approximation in the solution of the the non-linear EIT inverse problem, i.e., using the so-called linearized difference imaging scheme, resulting in a qualitative estimation of the conductivity change [84].

The aim of this study is to investigate whether EIT could be used for quantitative estimation of the three-dimensionally distributed water content in cement-based materials. In the experiments, moisture ingresses cement-based material containing fine aggregates. EIT measurements are collected during the moisture ingress, and used for reconstructing the 3D distribution of the electrical conductivity within the material. For the EIT reconstruction, the so-called absolute imaging scheme [113, 209, 27, 205] is adopted. The reconstructed electrical conductivity distributions are further converted to volumetric moisture content distributions, by using an experimentally-developed model. The results of EIT are compared with X-ray Computed Tomography (CT) and numerical simulations of unsaturated moisture flow. While the experiments are performed on cement-based materials, the methods developed in this work are also applicable to other porous materials.
3.3 Materials

3.3.1 General

For testing the feasibility of EIT for monitoring the moisture ingress in cement-based materials, two cylindrical mortar specimens were prepared. In the experiments, the moisture was added to the specimen from a PVC reservoir mounted on top of the specimen (Fig. 3.1). In one specimen, the reservoir was filled with water and in the second specimen, dilute solution of water and non-ionic radiocontrast agent (Iohexol, 120 mg Iodine/ml) was used. This was done to improve the contrast between the background and the regions of moisture ingress in X-ray CT imaging [191].

![Figure 3.1: (a) Photograph of the specimen and locations of the electrodes, (b) prepared specimen.](image)

3.3.2 Materials and sample preparation

The specimens used in this work were made of Portland cement mortar. The mortar was made with ordinary Type I Portland cement and fine aggregate consisting of natural river sand. The water-to-cement ratio (w/c) of the mortar was 0.60 and its total volumetric aggregate content was 40%. The high w/c and low aggregate content (high cement paste content) were used to accelerate the rate of moisture ingress and to reduce the test duration. The mortar mixture was prepared according to ASTM C192-06 [9]. A circular cylinder of diameter 10.20 cm and height 20.30 cm was cast from the mixture. The cylinder was demolded after 18 hours and cut in half to create the two specimens for the experiments.

After cutting, the specimen was moved to an oven at 50°C for 5 hours, and then sealed in two layers of plastic bags and placed inside an environmental chamber at 23°C for 21 days.
This process was carried out to achieve a relatively uniform moisture content throughout the specimen. The uniform initial moisture content was not necessary for EIT measurements, but was considered to improve the contrast in X-ray CT images. Furthermore, the corroboration of the experimental results with the flow simulation required the knowledge of the initial moisture content. The initial moisture content was determined experimentally by completely drying separate specimens conditioned using the same procedure; the conditioning resulted in an initial moisture content of $\theta_i = 0.07$.

The electrodes used in this work were made of colloidal silver paint which was applied to the surface of the specimen using a small brush. The colloidal silver paint had a low resistivity and was fast drying [153]. A total of 24 square electrodes (with dimensions of $1.30 \, \text{cm} \times 1.30 \, \text{cm}$) were painted on the perimeter of the specimen. The electrodes were arranged in 3 rings of 8 equally spaced electrodes. Fig. 3.1a shows the specimen and the locations of the electrodes. After the silver paint had dried, an 18 gage wire was placed on the surface of the silver paint. Contact between the electrodes and wires was secured using electric tape and zip ties (Fig. 3.1b).

The water reservoirs were made of 5.0 cm long PVC pipes with internal diameters of 0.95 cm, and they were installed on the top of the specimens using fast-drying silicon-based caulking. The water reservoirs were positioned eccentrically 1.30 cm off-center. The purpose of this positioning was to induce asymmetric moisture ingress in the specimens and realize whether EIT reconstructions can capture the water source location and asymmetric flow within the specimens. After placing the water reservoirs, the cylinders were wrapped with transparent tape to prevent evaporation of water from the specimens’ surface during the test (Fig. 3.1b).

### 3.4 Electrical Impedance Tomography (EIT)

#### 3.4.1 Reconstruction methods in EIT

In Electrical Impedance Tomography (EIT), electric currents are injected into an object through a set of electrodes on the specimen’s boundary. Corresponding to each current injection, a set of electrode potentials/potential differences are measured with respect to a common ground or between electrodes. Based on the measured potentials, the distribution of the electrical conductivity inside the object is reconstructed. A variety of methods for the image reconstruction in EIT have been developed [22]. Broadly, two imaging methods are commonly used in EIT: difference and absolute imaging.

In difference imaging, the temporal change of the conductivity distribution is estimated based on a difference between potential measurements corresponding to two states: before and after the change. The difference reconstructions are often relatively tolerant to systematic mea-
surement and modeling errors, because the errors at least partly cancel out in the subtraction of the two data sets. However, in the conventional difference imaging scheme, the non-linear observation model of EIT (see below) is globally linearized; this can result severe bias in the reconstructed conductivity change, especially when the true conductivity change is large and/or if a good approximation for the initial conductivity is not available. In consequence, the linearized difference reconstructions are often only qualitative in nature [82, 205]. In [191], the linearized difference imaging was used for monitoring the water ingress in mortar; severe artifacts were observed, especially when the water ingress had caused a large change in the conductivity of the mortar with respect to the initial state. The problems associated with the linearized difference imaging can be avoided to an extent by using the recently proposed non-linear difference imaging approach [113, 114]. In the present study, however, absolute EIT imaging is used – aiming at quantitative reconstructions of the conductivity distributions.

In absolute imaging, the conductivity distribution is reconstructed by solving the full non-linear inverse problem of EIT. The absolute reconstruction usually requires iterative solution. Furthermore, unlike in difference imaging, the reconstructions are generally severely intolerant to modeling errors, and hence, accurate (and computationally expensive) numerical models are needed for modeling the measurements. Consequently, the computational cost of absolute EIT imaging is often significantly higher than that of difference imaging.

In this work, the EIT measurements are modeled by the Complete Electrode Model (CEM), which is the most accurate forward model in EIT to date [193, 37]. The CEM consists of the partial differential equation

$$\nabla \cdot (\sigma \nabla u) = 0, \quad x \in \Omega$$

and the boundary conditions

$$u + \xi_l \sigma \frac{du}{dn} = U_l, \quad x \in e_\ell, \quad \ell = 1, \ldots, L$$

$$\sigma \frac{du}{dn} = 0, \quad x \in \partial \Omega \setminus \bigcup_{\ell=1}^{L} e_\ell$$

$$\int_{e_\ell} \sigma \frac{du}{dn} dS = I_l, \quad \ell = 1, \ldots, L$$

where $\Omega$ is the target volume, and $\partial \Omega$ is its boundary, $\sigma$ is the electrical conductivity, $u$ is the electric potential, $\bar{n}$ is the outward unit normal, $e_\ell$ is the $l^{th}$ electrode, and $\xi_l$, $U_l$ and $I_l$, respectively, are the contact impedance, electric potential and total current corresponding to $e_\ell$. Moreover, the current conservation law must be fulfilled
\[ \sum_{l=1}^{L} I_l = 0 \] (3.5)

and the potential reference level must be fixed, for example by writing

\[ \sum_{l=1}^{L} U_l = 0. \] (3.6)

The forward solution of EIT – computing the electrode potentials \( U_l \), given the electrode currents \( I_l \) and the conductivity distribution \( \sigma \) – requires the solution of the CEM (4.1) - (4.6). In practice, the solution is approximated numerically, for example by using the Finite Element Method (FEM) [206, 210]. The finite element (FE) approximation was used also in the present work, leading to a numerical model \( U(\sigma) \) for the dependence between the electrode potentials and a discretized conductivity distribution \( \sigma \). Further, assuming an additive Gaussian noise, the observation model for the EIT measurements becomes

\[ V = U(\sigma) + e \] (3.7)

where \( V \) is a vector consisting of the measured electrode potentials, and \( e \) is the Gaussian-distributed noise \( e \sim \mathcal{N}(0, \Gamma_e) \). Here, \( \Gamma_e \) is the noise covariance matrix, which can usually be determined experimentally [87].

In principle, the reconstruction of the discretized conductivity distribution \( \sigma \) can be thought of as a non-linear fitting problem spanned by model (3.7), i.e., finding a vector \( \sigma \) such that the computed voltages \( U(\sigma) \) fit to the voltage measurement data \( V \). However, due to properties of the model \( U(\sigma) \), this is mathematically an ill-posed inverse problem. This implies that classical solutions – such as the least-squares estimate for \( \sigma \) – are practically always unstable and non-unique [95]. In this work, we adopted the so-called Tikhonov regularization [206] to the solution. Furthermore, we introduced constraints for the conductivity values [113], and estimated the conductivity as

\[ \tilde{\sigma} = \arg \min_{\sigma_{\text{min}} \leq \sigma \leq \sigma_{\text{max}}} \left[ \| L_e (V - U(\sigma)) \|^2 + p(\sigma) \right] \] (3.8)

where \( L_e \) is the Cholesky factor of the noise precision matrix \( \Gamma_e^{-1} \), i.e. \( L_e^T L_e = \Gamma_e^{-1} \), and \( p(\sigma) \) is a regularization function [208]. The function \( p(\sigma) \) is formulated such that it penalizes improbable features of \( \sigma \). For the influence of \( p(\sigma) \) on the solution of the inverse problem, see e.g. [86, 20, 208]. In the present study, \( p(\sigma) \) was constructed to accommodate the so-called smoothness-promoting regularization, which is particularly applicable to diffusive processes [113], such as moisture flow in porous media. The smoothness-promoting function \( p(\sigma) \) can be...
written as \( p(\sigma) = \| L_\sigma \sigma \|^2 \), where \( L_\sigma \) is spatially weighted discrete differential operator [91, 95, 94].

The constraints \((\sigma_{\text{min}} \leq \sigma \leq \sigma_{\text{max}})\) were selected based on experimentally determined physical limits for the electrical conductivity. First, the lower bound \( \sigma_{\text{min}} \) was chosen to be equal to the conductivity corresponding to the initial moisture content \( \theta_i = 0.07 \). This choice was made based on the knowledge that the ingress of moisture does not degrease the conductivity of the mortar. Secondly, the upper bound \( \sigma_{\text{max}} \) was chosen to be the electrical conductivity of the saturated material. The experiment for determining \( \sigma_{\text{min}} \) and \( \sigma_{\text{max}} \) using measurements of variably saturated mortar is reported below in Section 3.4.3.

The computations were performed using a MATLAB implementation which is an adaption of codes reported in [2, 152]. In the FE approximation of the forward model, a maximum element dimension of 1.75 mm was chosen, resulting in FE meshes with over 946,500 tetrahedral elements. For the Tikhonov regularized solution (3.8), Gauss-Newton method was used. The computations were performed utilizing parallel computing processes on eight quad-core processors using 32 Gb total memory and implementation of [47] to solve the systems of linear equations.

3.4.2 EIT measurement strategy

The EIT measurements were carried out using an in-house developed EIT equipment described in [84]. In all measurements, an alternating current with 0.10 mA amplitude and 40.0 kHz frequency was used. This frequency was chosen based on Electrical Impedance Spectroscopy (EIS) measurements; at frequency 40 kHz, the imaginary component of the impedance was at the minimum. The accuracy of the potential measurements was \( \pm 1.0 \times 10^{-8} \) V. In the EIT measurements, current was injected between electrodes \( i \) and \( j \) where \( i, j = \{1, \ldots, 24\} \) and \( i \neq j \). Corresponding to each current injection, potential measurements were taken with respect to a common ground. 561 current injections and 4488 potential measurements were taken for each set of EIT measurements.

3.4.3 Experimental material model of electrical conductivity for variably-saturated mortar

To quantify the moisture content using EIT, we used an experimental model of \( \theta = \theta(\sigma) \) that relates the electrical conductivity \( \sigma \) to the volumetric moisture content \( \theta \). For this aim, we first determined the relationship between the electrical conductivity and the equilibrium relative humidity \( RH \) (i.e., \( \sigma = \sigma(RH) \)). Secondly, we measured the relationship \( \theta = \theta(RH) \) between the volumetric moisture content and the equilibrium relative humidity, and finally, combined these two models to get the function \( \theta = \theta(\sigma) \). Note that the dependence of \( \theta \) on \( \sigma \) (or the
converse) in cement-based materials was shown to not exhibit hysteresis in [162].

To experimentally determine $\sigma = \sigma(RH)$, a total of six prismatic, 6.0 mm $\times$ 1.5 mm $\times$ 4.0 mm mortar specimens were cut from a mortar cylinder using a precision diamond saw. Stainless electrodes were mounted to the 1.5 mm $\times$ 4.0 mm surface of the specimens using conductive silver-based epoxy. The specimens were then suspended in an air-tight container containing saturated salt solutions of KCl, NaCl, Mg(NO$_3$)$_2$, K$_2$CO$_3$, and MgCl$_2$ which induce RH conditions of 84.0, 75.3, 52.8, 43.6, and 32.3%, respectively [70, 34]. Another specimen was submerged in water to reach saturation. After 5 days of conditioning, the electrical resistances of the specimens were measured in 24-hour intervals until no change in resistance was observed between three consecutive measurements. The electrical resistance $R$ was then converted to conductivity using the relation $\sigma^{-1} = R \frac{A}{L}$, where $A$ and $L = 6.0$ mm are, respectively, the cross-sectional area and the length of the specimen.

The desorption isotherm, $\theta = \theta(RH)$, was experimentally obtained using an automated sorption analyzer [211, 156]. The function $\theta = \theta(\sigma)$ was then obtained by a piecewise cubic interpolation [62] to the above mentioned experimental data. This interpolation method was selected to (i) create continuity between intermediate values of $\theta$ and (ii) preserve the curve shape at high levels of moisture saturation. The experimentally obtained data and fitted curve are shown in Figure 3.2.

![Figure 3.2: Fitted moisture retention curve for mortar using van Genuchten parameters](image)

Using the initial moisture content $\theta_i = 0.07$, the moisture content at saturation $\theta_s = 0.15$
and the above described model $\theta = \theta(\sigma)$, the minimum and maximum conductivity of the material were computed, resulting in values $\sigma_{\text{min}} = 0.28 \text{ mS/cm}$ and $\sigma_{\text{max}} = 1.5 \text{ mS/cm}$. These values were used as the lower and upper bound in Eq. (3.8).

### 3.5 X-ray CT imaging

To corroborate EIT reconstructions, X-ray Computed Tomography (CT) imaging was conducted using a full-scale medical CT scanner with a peak beam energy of 120 kV and intensity of 40-200 mA (Fig. 3.3). In the CT scanner, the X-ray tube rotates perpendicularly to the circular cross-section of the specimen. As the fan beam rotates around the specimen, detectors on the opposite side are activated and measurements are taken. Upon completing a full rotation, the X-ray absorption coefficient $\mu(\text{mm}^{-1})$ is computed in voxels within the measured slice. X-ray radiation transmitted through the specimen is related to $\mu$ via the Lambert-Beer law:

$$I_x = I_0 \exp \left( - \int \mu d\ell \right)$$

where $I_x$ is the intensity of the transmitted X-ray passing through the specimen, $I_0$ is the incident X-ray intensity, and $\ell$ is the arc length variable along the line connecting the X-ray source and detector.

The voxel values of the CT images, $\mu - \mu_{\text{water}}$, were normalized by $\mu_{\text{water}} - \mu_{\text{air}}$ to get Hounsfield numbers $H$ is defined by [57]:

$$H = 1000 \times \frac{\mu - \mu_{\text{water}}}{\mu_{\text{water}} - \mu_{\text{air}}}.$$  \hspace{1cm} (3.10)\hspace{1cm}

Further, the spatial distribution of the volumetric moisture content $\theta$ was computed from the Hounsfield numbers [199]:

$$\theta = \frac{H_s - H}{1000},$$

where $H_s$ is the Hounsfield value of a saturated material. Here, the value of $H_s$ was taken from H values corresponding to voxels directly below the water reservoir, where the material was assumed to be completely saturated [156, 154].

In this experiment, only the specimen where the absorbed water contained the radiocontrast agent (Iohexol) was imaged with X-ray CT. As pointed out in [191], the sensitivity of CT does not allow for monitoring the absorption of plain water in this medium and geometry. The specimen was scanned at times 1, 2, 4 and 22 hours after the start of the water ingress. 2D slices were taken through the horizontal and vertical cross sections in 0.6 mm slices. CT images were analyzed using digital imaging software [1].
3.6 Numerical simulation of unsaturated moisture flow

3.6.1 General

Isothermal unsaturated moisture flow in porous media was simulated using Richards’ Equation [24, 166]:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left( K(h) \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K(h) \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K(h) \frac{\partial h}{\partial z} + 1 \right)$$

(3.12)

where $K = K(h)$ (mm/hour) is the unsaturated hydraulic conductivity, $\theta$ (mm$^3$/mm$^3$) is the volumetric moisture content, $h$ (mm) is the pressure head, and $x$, $y$, and $z$ (mm) are spatial coordinates. In this work finite element approximation of Eq. (4.10) was used to simulate the moisture flow in mortar.

3.6.2 Material model

In general, the unsaturated hydraulic conductivity is expressed as the product of the relative hydraulic conductivity $K_r$ and the saturated hydraulic conductivity $K_s$, such that $K = K_r K_s$. For unsaturated porous media, $K_r$ is described by Mualem’s equation [135]:

$$K_r = \Theta I \left[ \frac{1}{\int_0^\Theta \frac{1}{h(x)} dx} \right]^2$$

(3.13)
\[ \Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \]  
(3.14)

where \(0 \leq \Theta \leq 1.0\) is the effective material saturation, \(\theta_r\) is the residual moisture content where \(\theta_r = 0\) is generally considered as an appropriate assumption for cement-based materials [156, 155], \(\theta_s\) is the saturated moisture content that is measured experimentally in this work (\(\theta_s = 0.15\)), \(I\) is the tortuosity and pore connectivity parameter; in this work \(I = -9.0\) is taken from [187]. Discussion of \(I\) in cement-based materials is provided in [13] and [160]. In this work, saturated hydraulic conductivity \(K_s = 5.0 \times 10^{-3}\) (mm/hr) is obtained experimentally using Darcy’s Law and the procedure in [70].

In order to calculate the integrals in Eq. (6.4), the effective material saturation is expressed as a function of the pressure head, \(\Theta = \Theta(h)\) using the van Genuchten model [203, 204]:

\[ \Theta = \frac{1}{1 + (\alpha h)^n} \quad m = 1 - \frac{1}{n} \]  
(3.15)

where \(\alpha\) (mm\(^{-1}\)) and \(n\) (–) are fitting parameters. For cement-based materials, instead of expressing water retention as \(\Theta = \Theta(h)\), the material sorption isotherm is generally obtained experimentally as \(\Theta = \Theta(RH)\), where \(RH\) denotes relative humidity. In this work, the desorption isotherm was experimentally measured using an automated sorption analyzer [211, 156] (see Section 3.4.3) For simplicity we neglected the effect of hysteresis. To convert the experimentally obtained isotherm \(\Theta(RH)\) to the moisture retention curve as \(\Theta(h)\), the Kelvin-Laplace Equation is used [155, 108]:

\[ h = \frac{\rho_w R_s T}{m_w} \ln(RH) \]  
(3.16)

where \(\rho_w\) (g/mm\(^3\)) is the density of water, \(R_s\) (8.845 JK\(^{-1}\)mol\(^{-1}\)) is the universal gas constant, and \(m_w\) (g/mol) is the molecular weight of water. By fitting the model in Eq. (4.13) to the water retention curve \(\Theta(h)\), van Genuchten parameters \(\alpha = 2.63 \times 10^{-2}\) (mm\(^{-1}\)) and \(n = 1.77\) were obtained. The experimentally obtained data points and the fitted van Genuchten model are shown in Figure 4.4.

### 3.6.3 Simulation of moisture flow

The moisture flow in the specimen was modeled using a commercially available Finite Element Software HYDRUS 3D [215]. Zero-flux boundary conditions were considered at all surfaces except the surface from which water penetrated (water reservoir), which was modeled as a 9.5 mm diameter circle saturated throughout the simulation. Uniform initial moisture content, \(\theta_i = 0.07\) was selected based on the experiments described in Section 3.3.2. The Finite element
mesh consisted of tetrahedral elements with a maximum dimension of 4 mm. The finite element model was solved in terms of moisture content.

3.7 Results and discussion

Figures 4.7 and 3.6 show the results of the experiment where the dilute solution of water and Iohexol was absorbed to a mortar specimen. The left column of Fig. 4.7 illustrates the 3D electrical conductivity distribution reconstructed based on EIT measurements after 1, 2, 4 and 22 hours of moisture penetration. In the images, the black rectangles mark the electrodes attached on the surface of the specimen. The series of EIT reconstructions clearly shows the ingress of moisture: After 1 hour of moisture ingress, a small volume directly under the water reservoir features increase of the electrical conductivity; in the subsequent time intervals, the volume with increased conductivity gets larger. Also the value of the conductivity under the water reservoir increases over time, being close to conductivity at saturation, $\sigma_s = 1.5 \, \text{mS/cm}$, after 22 hours of moisture ingress.

The EIT-based estimates for the 3D volumetric moisture content $\theta$ at times 1, 2, 4 and 22 hours are shown in the right column of Fig. 4.7. These moisture content estimates were computed from the reconstructed 3D conductivity distributions $\sigma$ using the experimentally developed model $\theta = \theta(\sigma)$ described in Section 3.4.3. While the reconstructed conductivity distributions in the left column illustrate the ingress of moisture through the specimen qualitatively, the 3D
volumetric moisture content estimates allow for quantifying the moisture ingress. For example, the reconstructions of $\theta$ show that the moisture content is approximately 0.12 directly below the water reservoir after 1 hour of moisture ingress, and is nearly saturated ($\theta_s = 0.15$) after 22 hours of moisture ingress, while the background moisture content remains at the initial value 0.07. Qualitatively, the spatial and temporal gradients of $\theta$ look somewhat different from those of $\sigma$. This difference results from the non-linearity of the model $\sigma = \sigma(\theta)$.

The left column of Fig. 3.6 represents the EIT-based reconstructions of the 3D volumetric moisture content $\theta$ on a vertical 2D plane crossing the center of the water reservoir and extending to the exterior of the specimen. The right column shows X-ray CT images at the respective times. In these images, the water reservoir appears in the center of the top surface, because the 2D slice crossing the center of the water reservoir is off-centric with respect to the specimen; this is due to the orientation of the sample during the CT scan (Fig. 3.3). Also the X-ray CT images show the increase of $\theta$ directly below the water reservoir, and the value of $\theta$ in this region is close to the saturation value 0.15 at times 1 h and 2 h. However, in the 4 h and 22 h CT images, the value of the moisture content has decreased under the water reservoir, indicating a low sensitivity of CT to the water content with this specimen size. Moreover, the X-ray CT images presented here detect only high levels of saturation (similarly to X-ray images in [155]). The CT images do not show the presence of low levels of saturation because of the large sample size used (10.20 cm $\times$ 20.30 cm cylinder). Some previous studies using X-ray imaging (e.g., [170] and [171]) showed high resolution images of unsaturated moisture flow in cement-based material; however, the specimen sizes were small (maximum dimension of 5.5 cm in cement-based specimen tested). These results demonstrate that EIT is capable of imaging the moisture flow in a specimen, the size of which exceeds the limit of a regular CT scanner.

Figure 3.7 shows the results corresponding to the experiment where plain water was absorbed into a mortar specimen. The left column illustrates the volumetric moisture content $\theta$ reconstructed using EIT, and the right column shows $\theta$ computed by moisture flow simulation specified in Section 4.4.3. All images represent the vertical 2D cross-sections of the corresponding 3D distributions. The EIT reconstructions show a good correspondence with the moisture flow simulation. Indeed, the ingress of moisture predicted by the flow simulation is captured well by EIT, and the size and shape of the (nearly) saturated volume $\theta \approx 0.15$ in EIT-based images are close to those in the simulation-based images. Also the shapes of intervals with lower saturation in EIT-based reconstructions of $\theta$ compare relatively well with those in the simulations.

The addition of the radiocontrast agent (Iohexol) increases the viscosity and surface tension of water, and thus, the flow of the diluted solution in porous media is slower than the flow of plain water. The capability of EIT to distinguish between flow rates of these two liquids was shown in [191]. The comparison between the left columns of Figs. 3.6 and 3.7 further confirms
Figure 3.5: Results of the experiment with dilute solution of water and Iohexol; 3D EIT reconstructions depicting electrical conductivity ($\sigma$, left column) and volumetric moisture content ($\theta$, right column) for moisture ingress at: (a) 1 hour, (b) 2 hours, (c) 4 hours (d) 22 hours.
Figure 3.6: Results of the experiment with dilute solution of water and Iohexol; 2D slices of the EIT-based 3D reconstructions of the volumetric moisture content (left column) and CT-based images of the volumetric moisture content (right column) at: (a) 1 hour, (b) 2 hours, (c) 4 hours (d) 22 hours
Figure 3.7: Results of the experiment with plain water; 2D slices of the EIT-based 3D reconstructions of the volumetric moisture content (left column) and moisture flow simulation-based images of the volumetric moisture content (right column) at: (a) 1 hour, (b) 2 hours, (c) 4 hours, (d) 22 hours.
this; especially, the volume of the saturated mortar is consistently larger in Fig. 3.7 than in the respective times in Fig. 3.6.

3.8 Summary and conclusions

In this paper, we investigated whether Electrical Impedance Tomography (EIT) could be used to quantitatively monitor 3D moisture flow in cement-based materials. For this aim, we conducted an experiment where mortar specimens were imaged with EIT during the ingress of moisture. The so-called absolute imaging scheme was used to reconstruct the 3D distributed electrical conductivity within the mortar. The reconstructed electrical conductivity distributions were further converted to volumetric moisture content distributions, by using an experimentally-developed model. One of the samples was simultaneously imaged by a regular X-ray CT scan. Moreover, the results of EIT were corroborated by a numerical simulation of unsaturated moisture flow.

EIT captured the moisture flow in mortar and provided quantitative information on volumetric moisture content. The EIT-based estimates for the moisture content compared well with numerical simulations of unsaturated moisture flow. In contrast to X-ray CT images, which showed only highly saturated material, EIT reconstructions provided a good resolution at various levels of saturation. In the previous work [191], the difference imaging scheme was used to visualize moisture flow in cement-based materials, and significant artifacts were observed at the late stages of moisture flow. In the present work, however, the use of application-specific absolute imaging eliminated the artifacts in the reconstructions at late stages of moisture ingress, since, unlike difference imaging, absolute imaging is not based on the assumption of small changes in the electrical conductivity with regards to a reference state. Based on these findings, EIT shows promise for becoming a tool for imaging moisture flow in cement-based materials non-destructively and quantitatively. Moreover, the developed procedure for quantifying the moisture content using EIT is also applicable for other porous media.
Chapter 4

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

4.1 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.
4.2 Introduction

The resistance of concrete structures to the ingress of moisture and aggressive ions is commonly considered a measure of their durability [153, 81]. Cracking creates preferential pathways for moisture and aggressive ions to penetrate the bulk material and decrease the durability of concrete structures [70, 5, 43]. 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. [172] used 2D X-ray radiography to monitor moisture penetration in brick with discrete cracks to validate moisture flow simulations. Roels and Carmeliet [170] later used a 2D X-ray radiography technique to study homogeneous and non-homogeneous material with micro-scale discrete cracks. Pour-Ghaz et al. [155, 154] corroborated numerical simulations of unsaturated moisture flow with 2D X-ray radiography to assess moisture movement in a saw-cut. Kane-matsu et al. [96] 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. [31] 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. [63] investigated self-healing of cracks in low-permeability concrete using X-ray CT imaging. Recently, Li et al. [111] 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 cementitious 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 [84, 127].

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 between electrodes were performed. For example, McCarter and coauthors [130, 126, 129, 128] embedded electrodes at different vertical depths to detect the depth of the moisture ingress. In the approach proposed by McCarter et al. [128], 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. [163] 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 [44, 28, 29] 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 [51]; the ERT reconstructions were corroborated with Ground Penetrating Radar (GPR). In [84] 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 [191] ERT was shown to be capable of qualitatively imaging 3D moisture flow in large dimensional objects made of cement-based materials, and in [189], 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 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 [88, 98]. However, due to the diffusive nature of ERT, its spatial resolution is usually low [55], 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 enables 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 [106, 155]; 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.

4.3 Materials and sample preparation

4.3.1 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 Figures 4.1a and 4.1b, respectively. The three specimens with discrete cracks were damaged using split-tension loading and are shown in Figure 4.2. 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.

4.3.2 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 [232]. 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 [9].

To create the physically-simulated cracks (shown in Figures 4.1a and 4.1b), 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 hours, 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 hours and cut in half using a wet saw to create the specimens used in ERT tests. In the case of the specimen with the cylindrical through-crack, the bottom of the specimen was secured to a PVC plate using silicon caulking to ensure that the bottom of the specimen was water-tight.

![Specimens](image)

Figure 4.1: Specimens with physically-simulated cracks; (a) specimen with cylindrical through-crack and (b) specimen with plate-like crack.

Due to the high w/c ratio, specimens were saturated after demolding at 24 hours. The specimens were moved to an oven at 50°C for 5 hours to reduce their moisture content. The specimens were then sealed in two layers of plastic bags and placed inside an environmental chamber at 23°C for at least 30 days to achieve uniformity in the distribution of moisture content. The resultant volumetric moisture was determined to be \( \theta_i = 0.07 \) by drying a set of identically-conditioned specimens of the same material and geometry. It should be noted that \( \theta_i \) was determined from specimens that did not include cracks. However, it can be safely assumed that \( \theta_i \) was 0.07 also in the specimens with physically-simulated cracks.

After conditioning, the specimens without physically simulated cracks were damaged using the split-tension loading similar to ASTM C496 [10]. In this procedure, each cylindrical mortar specimen was loaded along the length of the specimen with a diametral compressive force. Such a load induces tensile stresses and therefore splitting along the loading plane. Displacement-controlled loading at 0.05 cm/min was used to generate cracks in these specimens.
Since the discrete cracks were difficult to observe in photographs due to the narrow crack widths, the photographs of the specimens were converted to grey scale and then binary images (Figure 4.2 using image analysis software [180]. In the image analysis, the thresholding method with an arbitrary threshold value (clip level) was used to convert the images from grey scale to binary [173]. This, overall, resulted in overestimation of the actual crack width, which was a function of the clip level. The purpose of Figure 2 is only to provide a visualization of cracks and their locations and to qualitatively illustrate the differences between the crack widths.

Figure 4.2: Binary images of specimens with discrete cracks; (a - c) top view of cracked specimens and (d - f) side view of cracked specimens.

4.3.3 Preparation of the ERT samples and water reservoirs

The electrodes used in this work were made of colloidal silver paint which was applied to the surface of the specimen using a small brush. The colloidal silver paint has a low resistivity and is fast drying, making it a suitable material for "painted" electrodes [153, 158]. A total of 24 square electrodes (with dimension of 1.30 cm × 1.30 cm) were painted on the outer surface of the cylindrical specimens. The electrodes were arranged in three equally spaced 8-electrode
rings. Figure 4.3a shows one of the specimens and the locations of the electrodes. After the silver paint electrodes had dried, a 14-gage wire was connected on the surface of each electrode using electric tape. Finally, the connection between electrodes and wires was force-secured using zip-ties.

For specimens with physically-simulated cracks, custom water reservoirs matching the shape of physically-simulated cracks were made from PVC. For specimens with discrete cracks, circular cylindrical PVC pipe water reservoirs were used; they were placed 2.0 cm off center to induce asymmetric water flow in the cracks. The reservoirs had a height of 5.0 cm and an internal diameter of 1.8 cm. A fully-prepared ERT specimen is shown in Figure 4.3b.

![Figure 4.3: Example of a specimen used in ERT testing: (a) location of the electrodes, (b) fully-prepared ERT specimen, and (c) isometric view including the water reservoir.](image)

### 4.4 Methods

#### 4.4.1 Electrical resistance tomography

In Electrical Resistance Tomography (ERT), a set of electrodes is installed on the surface of an object. Electric currents are applied between electrode pairs and resulting potential differences (voltages) are measured between multiple pairs of electrodes. Based on these voltage measurements, the distribution of the electrical conductivity in the object is reconstructed. ERT is a special case of Electrical Impedance Tomography (EIT), an imaging modality which uses both the electrode potential amplitudes and phase shifts between the sinusoidal potentials and the injected currents to reconstruct the electrical admittivity distribution; in ERT, the capacitive effects are neglected [99].

Mathematically, the reconstruction problem in ERT is a non-linear ill-posed inverse problem
in the sense that it may not yield stable or unique solutions and generally requires some sort of regularization. A variety of ERT reconstruction methods have been developed [22]. Broadly, difference imaging and absolute imaging are the most commonly used schemes. In difference imaging, the change in electrical conductivity is reconstructed from potential measurements corresponding to two states. One advantage of difference imaging is its robustness to modeling and systematic measurement errors, because the errors partially cancel due to subtraction of the two data sets. Difference imaging, however, is often qualitative and has a very low resolution due to the linearization of the nonlinear estimation problem [209]. In contrast to difference imaging, absolute imaging quantitatively reconstructs conductivity by solving the full non-linear ERT problem.

In this work, the ERT reconstructions were computed within the absolute imaging framework. However, because the target of primary interest in this work was the moisture content, the crack pattern within the specimen was considered as an auxiliary unknown, which was not explicitly modeled/estimated – instead, the initial conductivity was modeled as homogeneous, and the inhomogeneity related to cracking was accounted for only via introducing an approximative modeling error term which was calculated based on reference ERT measurements of the cracked specimens before the water ingress. This approach, adopted from [83], circumvents the drawbacks of the standard reconstruction methods, namely: 1) errors caused by linearization of the highly non-linear model in standard difference imaging, and 2) the difficulty of the standard absolute reconstruction problem, associated with the high complexity of the conductivity distribution in the presence of both unsaturated and saturated cracks. For an alternative, non-linear difference imaging -based approach to account for the inhomogeneity of the background conductivity, see [113].

To solve the inverse problem of ERT, a forward model is needed. The most accurate forward model for the ERT measurements, known to date, is the Complete Electrode Model [37, 193]. The CEM consists of the partial differential equation

\[ \nabla \cdot (\sigma \nabla u) = 0, \quad x \in \Omega \] (4.1)

and the boundary conditions

\[ u + \xi_\ell \sigma \frac{du}{dn} = U_\ell, \quad x \in e_\ell, \ \ell = 1, \ldots, L \] (4.2)

\[ \sigma \frac{du}{dn} = 0, \quad x \in \partial \Omega \setminus \bigcup_{\ell=1}^L e_\ell \] (4.3)

\[ \int_{e_\ell} \sigma \frac{du}{dn} dS = I_\ell, \quad \ell = 1, \ldots, L \] (4.4)
where $\Omega$ is the target volume, and $\partial \Omega$ is its boundary, $\sigma$ is the electrical conductivity, $u$ is the electric potential, $\bar{n}$ is the outward unit normal, $e_l$ is the $l^{th}$ electrode, and $\xi_l$, $U_l$ and $I_l$, respectively, are the contact impedance, electric potential and total current corresponding to $e_l$. Moreover, the current conservation law must be fulfilled

$$\sum_{l=1}^{L} I_l = 0 \quad (4.5)$$

and the potential reference level must be fixed, for example by writing

$$\sum_{l=1}^{L} U_l = 0. \quad (4.6)$$

To approximate the solution of the CEM (Eqs. (4.1 - 4.6)) for an object of arbitrary geometry we used the Finite Element Method (FEM) [206, 210]. Assuming a Gaussian noise model, the observation model for the ERT measurements gets the form

$$V = U(\sigma) + \epsilon \quad (4.7)$$

where $V$ is a vector consisting of the measured electrode potentials, $U(\sigma)$ is the finite element (FE) -based approximation for the mapping between a discretized conductivity distribution $\sigma$ and electrode potentials $V$, and $\epsilon$ is the Gaussian-distributed noise. For details of the forward model, we refer to [210].

Reconstructing $\sigma$ from potential measurements $V$ is an ill-posed inverse problem. This means that classical solutions, such as least-squares estimate for $\sigma$, are practically always non-unique and extremely intolerant to measurement noise and modeling errors [95]. Due to the ill-posedness, we employed so-called Tikhonov regularization [206], and estimated $\sigma$ as a solution of the following constrained minimization problem

$$\hat{\sigma} = \arg\min_{\sigma > 0} \left[ ||L_\epsilon(V - U(\sigma) - \epsilon)||^2 + p(\sigma) \right] \quad (4.8)$$

where $L_\epsilon$ is the Cholesky factor of the noise precision matrix and $p(\sigma)$ is a regularizing function (see below). Further, $\epsilon$ is an approximative modeling error term defined by

$$\epsilon = V_{\text{ref}} - U(\sigma_{\text{ref}}) \quad (4.9)$$

where $V_{\text{ref}}$ is a vector consisting of the ERT measurements at the reference state (i.e., before introducing water) and $U(\sigma_{\text{ref}})$ is a vector of computed potentials corresponding to $\sigma_{\text{ref}}$, a homogeneous estimate for the of non-homogeneous conductivity of a specimen at the reference
state. Here, the homogeneous estimate was chosen to be $\sigma_{ref} = 0.28 \, \text{mS/cm}$, the electrical conductivity resulting from the sample conditioning described in Section 4.3.2. Thus, the error term $\epsilon$ accounted for the discrepancy in the electric voltages resulting from the presence of the cracks and the non-uniformity of the initial moisture content distribution. For further discussion of the error model, see [83].

The regularization function, $p(\sigma)$, carries prior information on the conductivity, and is generally formulated such that it penalizes for undesirable or improbable features of $\sigma$. Therefore, $p(\sigma)$ has a significant influence on the solution of the inverse problem [86, 20]. In this work, smoothness-promoting regularization [149] was used, as it is particularly applicable to diffusive processes, such as moisture flow in porous media. In smoothness-promoting regularization, the regularizing function takes the form $p(\sigma) = \alpha \|L_\sigma\|^2$, where $L_\sigma$ is a spatially weighted discrete differential operator and $\alpha$ is a parameter which controls the weight of the side constraint in the solution [95, 94]. Finally, in the solution (4.8), the constraint $\sigma > 0$ was written based on the physical constraint that electrical conductivity is always positive.

It should be noted herein that in cases of physically-simulated cracks that were large and had known geometries, it would have been possible to model cracks as boundaries in the FE model [97], similarly to models used for moisture flow simulations in next section. However, in the specimens featuring load-induced cracks – as well as in the potential applications of the method – the crack shapes are not known. For this reason, the cracks boundaries were not modeled in any of the the FE geometries.

To reconstruct the discretized conductivity distribution $\sigma$ by solving the constrained optimization problem (4.9), the Gauss-Newton method was used. The forward model was solved using tetrahedron elements with a maximum dimension of 2.0 mm, resulting in 828,188 elements. The mesh size was selected based on separate grid coarsening studies; the chosen grid was found to ensure sufficient accuracy of the ERT forward model while maintaining a feasible computational expense. The accuracy of the forward model affects the resolution of ERT reconstructions. It should be noted, however, that the resolution is also affected by various other factors, e.g., placement of the electrodes, measurement noise level, and the regularization methods used in the image reconstruction. Generally, the resolution of ERT is relatively low, due to the ill-posedness of the associated inverse problem [95].

The ERT forward model geometries were modeled as solid cylinders. All ERT calculations were carried out using MATLAB and an adaptation of [2, 152] coupled with parallel processes on 12 quad-core processors using 48 Gb of total memory and implementation of [47] to solve the systems of linear equations.
4.4.2 ERT measurement strategy

The ERT measurements were carried out using an in-house developed ERT equipment described in [84]. In all measurements, an alternating current with 0.10 mA amplitude and 40 kHz frequency was used. This frequency was chosen based on Electrical Impedance Spectroscopy (EIS) measurements; at frequency 40 kHz, the imaginary component of the impedance was at the minimum. We note herein that the selected frequency based on the EIS measurements, applies only the material tested in this work since the frequency at which the imaginary component of the impedance is minimum (the cutoff frequency) changes depending on the microstructure of the material [38, 198]. One of the factors affecting the cutoff frequency is the moisture content. The moisture content changes, of course, during an ingress experiment and may affect the cutoff frequency. Therefore, the chosen cutoff frequency based on the initial condition of the material (40 kHz here) may not be the most appropriate frequency during the entire duration of the experiment. Further investigation on the effect of varying the measurement frequency during the experiment is required to fully realize the effect of cutoff frequency on the ERT reconstructions.

The accuracy of the potential measurements was $\pm 1.0 \times 10^{-8}$ V. In the ERT measurements, current was injected between electrodes $i$ and $j$ where $i, j = \{1, ..., 24\}$ and $i \neq j$. Corresponding to each current injection, potential measurements were taken with respect to a common ground. A total of 561 current injections and 4488 potential measurements were taken for each set of ERT measurements.

4.4.3 Numerical simulation of unsaturated moisture flow

Richards’ Equation

Isothermal unsaturated moisture flow in porous media was simulated using Richards’ Equation [24, 166]:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left( K(h) \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K(h) \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K(h) \frac{\partial h}{\partial z} + 1 \right)$$  \hspace{1cm} (4.10)

where $K = K(h)$ (mm/hour) is the unsaturated hydraulic conductivity, $\theta$ (mm$^3$/mm$^3$) is the volumetric moisture content, $h$ (mm) is the pressure head, and $x$, $y$, and $z$ (mm) are spatial coordinates. As described in [179], air voids affect the transport properties of cement-based materials. In Equation (4.10), however, air diffusion and dissolution are neglected and only capillary suction is simulated. We note that air diffusion and dissolution occur primarily in late stages of moisture ingress [71, 34, 81], while capillary suction is the main governing transport mechanism at early stages of unsaturated moisture ingress [124]. Since this work considers moisture transport for durations less than 24 hours, neglecting the effects of air diffusion and dissolution can be considered an appropriate approximation.
Material model

Commonly, the unsaturated hydraulic conductivity is expressed as the product of the relative hydraulic conductivity, $K_r$, and the saturated hydraulic conductivity, $K_s$, such that $K = K_r K_s$. Here, $K_s$ was measured experimentally as described in Section 4.4.3. For unsaturated porous media, Mualem’s equation [135] is used to describe $K_r$:

$$K_r = \Theta I \left[ \frac{\int_0^\Theta \frac{1}{h(x)} \, dx}{\int_0^1 \frac{1}{h(x)} \, dx} \right]^2$$

(4.11)

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

(4.12)

where $0 \leq \Theta \leq 1.0$ is the effective material saturation and $\theta_r$ is the residual moisture content. $\theta_r = 0$ is generally considered as an appropriate assumption for cement-based materials [156, 155]. $\theta_s$ is the saturated moisture content that was measured experimentally. $I$ is the tortuosity and pore connectivity parameter and in this work $I = -9.0$ was taken from [187]. In [187], $I$ was determined by fitting the results of numerical simulations to the experimentally obtained sorptivity data using the maximum likelihood least squares fitting approach. While the parameter $I$ has been described as the tortuosity and pore-connectivity parameter, in [135], this parameter is not, strictly speaking, a descriptor of classical tortuosity [120, 5] or pore connectivity [137]. Indeed, in works such as [102] and [160], it was argued that $I$ is fitting parameter with no physical meaning. Further discussion of $I$ in cement-based materials is provided in [13] and [160].

In order to calculate the integrals in Eq. (6.4), the effective material saturation was expressed as a function of the pressure head, $\Theta = \Theta(h)$. We used the van Genuchten model [203, 204], which is of the form

$$\Theta = \frac{1}{[1 + (\alpha h)^n]^m}, \quad m = 1 - \frac{1}{n}$$

(4.13)

where $\alpha$ (mm$^{-1}$) and $n$ are fitting parameters. For other models, see [26, 102]. For cement-based materials, instead of expressing water retention as $\Theta = \Theta(h)$, the material sorption isotherm is generally obtained experimentally as $\Theta = \Theta(RH)$, where RH denotes relative humidity. It should be noted that this work neglected hysteresis effect for simplicity. As mentioned by [231, 15] and [121] rewetting decreases the unsaturated and saturated hydraulic conductivities. This would imply that our model overestimated unsaturated hydraulic conductivity since we did not account for rewetting. Therefore, without knowing the rewetting isotherm there is some uncertainty regarding the extent to which the unsaturated hydraulic conductivity was decreased. To convert the experimentally obtained isotherm $\Theta(RH)$ to the moisture retention
curve as $\Theta(h)$, the Kelvin-Laplace Equation was used [155][108]:

$$h = \frac{\rho_w RT}{m_w} \ln(RH) \quad (4.14)$$

where $\rho_w$ (kg/m$^3$) is the density of water, $R = 8.845$ JK$^{-1}$mol$^{-1}$ is the universal gas constant, and $m_w$ (kg/mol) is the molecular weight of water. By fitting the model (4.13) to the water retention curve $\Theta(h)$, van Genuchten parameters $\alpha = 2.63 \times 10^{-2}$ (mm$^{-1}$) and $n = 1.77$ were obtained. Figure 4.4 shows the fitted van Genuchten model and experimentally obtained data points.

![Graph showing moisture retention curve](image)

**Figure 4.4: Moisture retention curve for mortar using van Genuchten fitting**

**Determination of moisture transport model parameters**

In this work, moisture flow simulations were only used to corroborate ERT reconstructions, and as such, simulation of moisture flow was not the main objective of this paper. We, therefore, only provide a brief description of the methods to obtain transport modeling parameters. Complete details of methods to simulate moisture flow can be found in [188, 187, 71, 211, 156, 155].

The saturated hydraulic conductivity $K_s$ was determined using an in-house developed equipment and the application of Darcy’s law following procedures in [70], yielding $K_s = 5.0 \times 10^{-3}$ (mm/hr). The saturated moisture content $\theta_s$ was determined from drying initially saturated specimens at 105°C for 48 hours, resulting $\theta_s = 0.15$. We note that by drying at 105°C
for 48 hours, \( \theta_s \) may be overestimated due to the potential dehydration of ettringite and other phases within the cement paste as well as the release of physically adsorbed water on the C-S-H gel. Further, the initial moisture content \( \theta_i \) was calculated using the drying procedure detailed in Section 4.3.2, and was determined to be \( \theta_i = 0.07 \). Finally, the desorption isotherm was experimentally measured using an automated sorption analyzer [211, 156]. A summary of the experimentally obtained parameters (\( K_s, \theta_i, \) and \( \theta_s \)) and van Genuchten modeling parameters (\( \alpha, n, I, \) and \( \theta_r \)) are provided in Table 2.1. The parameters shown in Table 2.1 were used in all simulations.

### Table 4.1: Material parameters

<table>
<thead>
<tr>
<th>w/c ( \frac{mm^3}{mm^3} )</th>
<th>( v_a \frac{mm^3}{mm^3} )</th>
<th>( K_s \frac{mm^3}{mm^3} )</th>
<th>( \theta_s \frac{mm^3}{mm^3} )</th>
<th>( \theta_i \frac{mm^3}{mm^3} )</th>
<th>( \theta_r \frac{mm^3}{mm^3} )</th>
<th>( I (-) )</th>
<th>( \alpha \frac{1}{mm} )</th>
<th>( n (-) )</th>
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<td>0.07</td>
<td>0</td>
<td>-9.0</td>
<td>0.026</td>
<td>1.77</td>
</tr>
</tbody>
</table>

Simulation of moisture flow in specimens with physically-simulated cracks

Commercially available Finite Element Software HYDRUS 3D [215] was used to simulate unsaturated moisture flow in specimens with physically-simulated cracks. Zero-flux boundary conditions were applied to all surfaces except the surfaces from which water penetrated. For both specimens, a Dirichlet boundary condition \( \Theta = 1.0 \) was written for the outer surface of the crack, i.e., the material in contact with water was modeled as fully saturated. The uniform initial moisture content \( \theta_i = 0.07 \) was considered, as discussed in Section 4.3. The model geometries are shown in Figure 4.5. The finite element mesh consisted of tetrahedral elements with a maximum dimension of 2 mm. The finite element model was solved in terms of moisture content.

### 4.5 Results and discussion

#### 4.5.1 ERT reconstructions of moisture flow in physically-simulated cracks

Figure 4.6 shows the results of the experiments and moisture flow simulations for specimens with physically-simulated cracks. Figure 4.6a corresponds to the specimen with the cylindrical physically-simulated through-crack, and Figure 4.6b to the plate-like crack. Both in Figure 4.6a and 4.6b, the first row represents the ERT-based reconstructions of the conductivity distribution \( \sigma \) after 1, 4, 12, and 24 hours of moisture ingress, and the second row shows the simulated water content \( \theta \) at the respective times. Note that the images representing \( \theta \) show the water
content within the computational domain, which excludes the contents of the cracks (cf. Fig. 4.5) – within the water-filled cracks, the water content is naturally equal to 1. Note also that the conductivity of the unsaturated mortar (0.95) is assigned as transparent in the images representing the conductivity distributions; this enables the visualization of the volumes of higher conductivity in 3D. The far left column in the figure shows top view of the specimens.

The ERT-reconstruction corresponding to time of 1 h water ingress in the specimen with cylindrical through-crack features a high conductivity in a volume, the shape and size of which are very similar to the crack; that is, ERT has successfully located the cylindrical crack in the saturated condition. The conductivity outside the crack is almost uniform and lower than within the crack, suggesting that water has not yet absorbed significantly to the surrounding material. The simulated water content $\theta$ at time 1 h is in agreement with this result, $\theta$ being above the initial moisture content (0.07) only in the close neighborhood of the cylindrical crack. In the subsequent time steps (4, 12 and 24 h), the volume with high conductivity increases steadily. The reconstructed conductivity distributions are again in a very good agreement with the moisture flow simulation, featuring mutually very similar shape in the volumes of high $\sigma$ and $\theta$. The series of images in Figure 4.6a suggest that ERT is able to capture the ingress of water in the surrounding material.

In the second experiment (Figure 4.6b), the plate-like crack is localized by ERT. The vertical dimension of the crack (2/3 of the specimen height) is traced relatively well, while tracing the length of the crack in horizontal direction is less successful. As noted above, ERT is generally an imaging modality with a relatively low resolution. Moreover, the resolution of ERT is generally not uniform within an object; the spatially dependent resolution is affected, e.g., by the geometry of the object, placement of the electrodes, and the regularization as well as other computational methods used in the image reconstruction [72]. Nevertheless, the series of images corresponding
to times 1, 4, 12 and 24 h shows the penetration of water to the material around the crack. Again, the ERT reconstructions correspond to the results of moisture flow simulation relatively well, supporting the ability of ERT to image water flow in cracked cement-based material.

We emphasize that the above comparison between the results of ERT and moisture flow simulation is only qualitative, because ERT reconstructions report electrical conductivity $\sigma$ (mS/cm), whereas simulations of moisture flow report the volumetric moisture content $\theta$ (mm$^3$/mm$^3$). Note that the relationship between $\sigma$ and $\theta$ is nonlinear [189].
Figure 4.6: 3D ERT reconstructions of the electrical conductivity $\sigma$ and simulated water content $\theta$ corresponding to 1, 4, 12, and 24 hours of ingress in: (a) mortar specimen with the physically simulated cylindrical through-crack, and (b) mortar specimen with the plate-like crack. Top view of each specimen is shown in the far left column.
4.5.2 ERT reconstructions of moisture flow in load-induced cracks

ERT reconstructions of the three specimens with loading-induced discrete cracks are visualized in Figures 4.7 and 4.8. While Figure 4.7 illustrates the reconstructed conductivity distributions as 3D contour plots, Figure 4.8 represents the conductivities on 2D horizontal slices at heights of 2, 4.5, 7, and 9.5 cm from the bottom of the specimens. In both figures, the results of the two fiber reinforced specimens are shown in the first two lines, and the results of the mortar specimen without fiber reinforcement in the third line. Again, in Figures 4.7 and 4.8, the conductivity of the unsaturated mortar (0.95) is assigned as transparent, to enable the visualization of the volumes of higher conductivity in 3D. The far left columns show the binary images of the top of the specimens.

For the first fiber reinforced specimen (Figures 4.7a and 4.8a), the ERT reconstruction corresponding to 15 min of water ingress shows increase of conductivity directly under the water reservoir and in a volume extending from the location of the reservoir towards the side surface of the cylindrical specimen – i.e., to the direction of the visible crack under the reservoir (cf. the binary image in Figure 4.7a, left). In the subsequent times (1, 4, 12 and 24 h), the volume of the high conductivity continues to extend, both horizontally and vertically. The increase of conductivity is clearly strongest along the crack (see especially Figure 4.8a). The reconstructed evolution of the conductivity has features that were expected for the ingress of moisture in a cracked fiber-reinforced specimen: a crack saturates when in contact with water, and acts as a source of water ingress for the surrounding material, similarly to the simple cases of physically simulated cracks in Figure 4.6. Here, however, the ERT images indicate that in the beginning of the experiment, only a portion of the crack gets saturated – north west direction from the reservoir, and not very deep vertically, yet the crack extends horizontally through the entire diameter and vertically through the entire height of the specimen (cf. Figure 4.2). This is also a plausible result, because the fiber reinforcement keeps portion of the cracks in the specimen narrow, and the narrowest parts of the cracks do not saturate as quickly as the wide part of the crack. Indeed, the volumetric flow rate in a parallel-plate crack \( Q_c \) has been shown to increase proportionally to the cubic power of crack width \( w_c \) [70], i.e \( Q_c \propto w_c^3 \). The observation of the conductivity increase being strongest along the crack over the time-series was also an expected result: It indicates that the crack offers a preferred pathway for the moisture ingress over the surrounding porous material.

In the case of the second fiber reinforced specimen (Figures 4.7b and 4.8b), the conductivity again increases quickly in the location of the crack under the reservoir (cf. the binary image in Figure 4.7b, left). Here, the region of increased conductivity covers the entire length of the crack in the horizontal direction already in the reconstruction corresponding to 15 min of water ingress. Vertically, however, the region of increased conductivity only about 1/3 of the specimen.
height, which is probably again due to a narrow crack width caused by the fiber reinforcement. However, the images of the reconstructed conductivity at times 1, 4, 12 and 24 h of water ingress show that the conductivity increases most strongly in the direction along the crack. Simultaneously, the volume of the increased conductivity spreads in all other directions, again indicating the capability of ERT to image the ingress of moisture in the material surrounding the crack.

In the last specimen (Figures 4.7c and 4.8c), the evolution of the conductivity distribution has mostly similar properties to the previous cases: the increase of conductivity along the crack, and spreading of the conductive region caused by the penetration of moisture to the cement-based material. The difference between this case and the previous two cases is that here, the conductivity increases rapidly within the entire extent of the crack under the water reservoir: The region of increased conductivity has already extended to the bottom of the specimen after 15 min of water ingress. This is again an expected result, because this specimen was not reinforced with fibers; it thus featured wider cracks which saturated rapidly.

In summary, the experiments with the specimens with loading-induced discrete cracks resulted ERT reconstructions which clearly illustrate the flow of moisture in a cracked cement-based material. In the absence of a proper corroboration method (such as an alternative imaging modality) for verifying the results, the ERT reconstructions of the specimens with loading-induced discrete cracks were only evaluated based on visual inspection of the crack pattern on the surfaces of the specimens. The reconstructed images are in a good agreement with the visual observation, and they conform well with the known properties of the unsaturated moisture flow in cement-based materials – indeed, the coupled moisture flow in cracks and the surrounding material observed in the ERT reconstructions can be characterized as a well-known mobile-mobile (dual permeability) moisture transport [188, 212, 43]. These results, together with the findings of the experiments reported in Section 4.5.1, strongly support the feasibility of ERT for imaging unsaturated moisture flow in cement-based materials with discrete cracks.
Figure 4.7: 3D ERT reconstructions of unsaturated moisture flow in discrete cracks for 15 minutes, 1, 4, 12, and 24 hours of ingress in: (a, b) mortar specimens with non-metallic fiber reinforcement and (c) the mortar specimen without fiber reinforcement. The water reservoir location and a binary image of the top of the specimen shown in the far left column.
Figure 4.8: 2D horizontal slices of 3D ERT reconstructions of unsaturated moisture flow in discrete cracks for 15 minutes, 1, 4, 12, and 24 hours of ingress in: (a, b) mortar specimens with non-metallic fiber reinforcement and (c) the mortar specimen without fiber reinforcement. The water reservoir location and a binary image of the top of the specimen shown in the far left column.
4.6 Summary and conclusions

Cracks provide preferential pathways for moisture to flow into cement-based materials. Cracking therefore significantly reduces material resistance to moisture ingress and, consequently, durability. Yet, few methods offer ample resolution to visualize moisture flow in cracked materials without significant testing constraints. The aim of this paper was to determine if ERT could be used to monitor 3D unsaturated moisture flow in cement-based material with discrete cracks. This topic was studied experimentally. In the first set of experiments, the mortar specimens contained physically-simulated cracks of known geometries, and the ERT reconstructions were compared with numerical simulations of unsaturated moisture flow. Next, mortar specimens with loading-induced cracks were subjected to moisture ingress. Two of these specimens were reinforced with non-metallic fibers, and one specimen was made of plain mortar. These materials were selected to alter the crack widths and permeability of cracks, with the intention to create different flow regimes. In the absence of a proper corroboration method, the ERT reconstructions of the specimens with loading-induced cracks were evaluated qualitatively based on visual observations and known properties of unsaturated moisture flow.

In all specimens, 3D moisture flow in cracks and the surrounding material was captured with ERT. Progressive flow of water in cracks was observed, confirming that ERT can be used to visualize differing rates of water ingress in cracks with dissimilar geometries and permeabilities. The results confirm that ERT is a feasible modality for imaging unsaturated moisture flow in cement-based materials with discrete cracks. The application of ERT to visualize moisture flow in cracks and the surrounding material may be extended to many cracked porous materials and various specimen geometries. In this work a cylindrical geometry was used, therefore, applicability of ERT to visualize features in irregular geometries requires further research. Especially, in the case of large geometries and geometries that constrain physical access for measurement (e.g., frames, beams, foundations, and dams) the use of advanced computational and approximation techniques may be necessary and requires further research.
Chapter 5

Modeling Water Absorption in Concrete and Mortar with Distributed Damage

5.1 Abstract

The deterioration rate of concrete structures is directly influenced by the rate of moisture ingress. Modeling moisture ingress in concrete is therefore essential for quantitative estimation of the service life of concrete structures. While models for saturated moisture transport are commonly used, concrete, during its service life, is rarely saturated and some degree of damage is often present. In this work, we investigate whether classical isothermal unsaturated moisture transport can be used to simulate moisture ingress in damaged mortar and concrete and we compare the results of numerical simulations with experimental measurements of water sorption. The effect of hysteresis of moisture retention is also considered in the numerical simulations. The results indicate that the unsaturated moisture transport models well simulate early stages of moisture ingress at all damage levels, where capillary suction is the prominent mechanism. At later stages of moisture transport, where air diffusion and dissolution have a more significant contribution, simulations that consider moisture hysteresis compare most favorably with experimental results.

5.2 Introduction

The rate of freeze-thaw deterioration, chemical attack, corrosion of reinforcement, and many other deleterious processes in concrete structures are strongly dependent on the rate of moisture ingress. The rate of moisture ingress is heavily influenced by the degree of saturation and the
presence of damage. Concrete, during its service life, is rarely saturated and some degree of
damage is often present (e.g., due to freeze-thaw). Distributed damage in concrete significantly
increases the rate and the amount of moisture ingress [70, 71, 227, 85, 6]. While unsaturated
moisture transport in concrete material has been studied (e.g. [116, 123, 81]), limited research
exists on unsaturated moisture transport in damaged concrete [132, 217, 134, 233, 67]. Specifi-
cally, modeling studies on unsaturated moisture transport in damaged cementitious material
are very scarce [202, 73, 32, 43]. In this paper, we investigate the accuracy of the classical
model (including hysteresis) for simulating unsaturated water absorption in damaged mortar
and concrete.

The majority of the previous studies on moisture transport in damaged cementitious mate-
rial were experimental in nature. These studies have shown that, for example, chloride migra-
tion (as tested by Rapid Chloride Permeability Testing) increases in concrete after subjecting
concrete to compressive loading above 75% of its compressive strength [175, 216] found that
water permeability generally increases with damage; Aldea et al. [6] found that discrete cracks
have a significant effect on water permeability; Rodriguez and Hooten [169] found that chloride
penetration increases in damaged samples, irrespective of the presence of mineral admixtures;
Picandet et al. [150] found that the permeability of discrete cracks increases proportional to the
cube of the crack opening displacement in specimens. They also showed that the use of fiber
reinforcement increases the crack tortuosity. In a recent study, the effects of distributed damage
on mass transport was shown to be dependent on the mechanisms of transport considered [70].

The previous experimental studies have offered significant insights as to the effect of damage
on the mass transport properties of damaged cement-based material. While a significant amount
of experimental data for damaged cement-based materials are available in the literature, the
numerical simulation of unsaturated moisture flow in damaged cement-based material is not well
studied. In contrast, numerous studies have simulated moisture flow in undamaged materials
(e.g., [90, 155, 18]). Numerical simulations are of significant interest since many service-life
prediction models need to account for the effects of damage characteristics which significantly
affect moisture flow in concrete structures [178].

Recent examples studying moisture flow simulations in damaged cementitious material in-
clude the followings. Grassl [73] developed a lattice model, modeling 2D fractured materials,
to simulate moisture flow in concrete with distributed cracks. Pour-Ghaz et al. [155] compared
simulations of unsaturated moisture flow from saw-cuts, an idealized crack, to X-ray radiog-
raphy images. Van Belleghem et al. [202]) compared flow regimes from numerical simulations
of unsaturated moisture flow in discrete cracks with X-ray images, showing good comparison
between the numerical model and X-ray images. These numerical investigations demonstrated
the feasibility of numerical simulations of unsaturated moisture flow in cement-based materials.
However, neither the effects of varying degrees of damage in the form of distributed cracks nor
the effect of moisture retention hysteresis have been studied.

The classical model describing unsaturated mass transport in porous media is Richards equation [166], modeling capillary suction. Richards equation has been identified as a valid model for mass transport in building materials (Wilson et al. [222]). Analytical solutions to Richards equation have been developed for simple geometries [30], (cf. Parlange et al.[145, 144] and Warrick et al. [218]). Analytical solutions are generally feasible in simple geometries subjected to simple boundary conditions. Practical applications, however, often requires numerical solution to Richards equation using, for example, the Finite Element Method. The Finite Element Method solutions of Richards equation have been used previously to analyze unsaturated moisture transport in concrete (e.g. [202, 155]). However, these studies investigated cementitious material with discrete cracks. Therefore the feasibility of using classical isothermal unsaturated moisture transport to model moisture ingress and moisture hysteresis in mortar and concrete with distributed damage remains an open question.

5.3 Numerical methods

5.3.1 General

In this paper, moisture absorption is modeled using the Richards Equation (Eq. 1) [166] for unsaturated moisture flow. Equation 1 is the classical governing differential equation for isothermal unsaturated flow

\[
\frac{d\theta}{dt} = \frac{d}{dx_i} \left[ K(h) \left( \frac{dh}{dx_j} + \delta_{ij} \right) \right]
\]

(5.1)

where \( K = K(h) (\text{mm/hour}) \) is the unsaturated hydraulic conductivity of the medium, \( \theta (\text{mm}^3/\text{mm}^3) \) is the volumetric moisture content, \( h (\text{mm}) \) is the pressure head, \( x_i (\text{mm}) \) is the spatial coordinate \((i, j = 1, 2, 3 \text{ for three-dimensional space})\), and \( \delta_{ij} \) is the Kronecker Delta function which accounts for the effect of gravity. Eq. 6.3 is generally solved using a numerical methods such as finite element method. In this work we have used a commercially available software (HYDRUS 3D) for this purpose and the details of modeling methods are discussed in the following section.

5.3.2 Material Model

The unsaturated hydraulic conductivity \( K \) in Eq. 6.3 1 is a function of capillary suction (i.e \( K = K(h) \)). Experimental measurements of unsaturated hydraulic conductivity are generally difficult and time consuming. These measurements are especially challenging for cement-based materials due to the fine pore size distribution resulting in high capillary suction at low water contents (Pour-Ghaz et al. [155]). Alternatively, the unsaturated hydraulic conductivity can be
expressed as a product of the saturated hydraulic conductivity, $K_s$, and the relative hydraulic conductivity, $0 < K_r < 1.0$ (i.e. $K = K_s K_r$). Such a model, commonly used in soil physics, has been shown to well-represent the unsaturated hydraulic conductivity in cement-based materials [181, 160]. The value of $K_s$ can be experimentally measured using Darcys law. The relative hydraulic conductivity is related to water content and capillary suction by Mualem’s model [135]

$$K_r = \frac{\int_0^\Theta \frac{1}{h(x)} \, dx}{\int_0^1 \frac{1}{h(x)} \, dx} \quad (5.2)$$

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (5.3)$$

where $0 \leq \Theta \leq 1.0$ is the effective material saturation, and $\theta_s$ and $\theta_r$ are the saturated moisture content and the residual moisture content, respectively. In this work, $\theta_s$ is experimentally obtained for each degree of damage and $\theta_r = 0$ [155]. Further discussion of $\theta_s$ is provided in the Materials and Methods section. $I$ is an empirical parameter which has been described as accounting for tortuosity and connectivity of pores [135]. Mualem proposed $I = \frac{1}{2}$ as an optimal value for 45 undisturbed soils; however, he noted that values for $I$ can take positive or negative values. Values for $I$ have been shown to range from -8.83 to 100 [177, 228, 183] Values of $I$ for cementitious materials and especially for damaged cementitious materials are not readily available. Schneider et al. [181] reported values of -3.0 and 35.2 for mortar and concrete, respectively. Poyet et al. [160] concluded that the values of $I$ can take positive or negative values, but are generally negative.

It should be noted that the choice of $\theta_r = 0$ is mainly for convenience since it does not introduce a significant modeling error and does not require elaborate measurements. In theory, the value of $\theta_r$ should correspond to the water content of the material at equilibrium with 11% relative humidity. This condition results in the formation of a monolayer of physically adsorbed moisture on calcium silicate hydrate (Alizadeh et al. [7], Feldman et al. [59, 60], Feldman and Sereda [58]) which can be only achieved under extreme drying conditions. In this work, we choose $\theta_r = 0$ following [155] to also avoid inconsistency in modeling between mortar and concrete since the actual value of $\theta_r$ for concrete is unknown for our materials.

In this study, values of $I$ are estimated by model training using maximum likelihood approach [107]. For such an approach the data need to be split into two sets: training and validation set. In this study only limited supply of experimental data is available. In such situations, using cross-validation methods may provide more accurate solutions of $I$. However, cross-validation methods can be very computationally expensive due to the computational cost of moisture transport simulations. We therefore use the maximum likelihood least squares fitting approach.
by splitting the experimental data into training and validation set using random number generators. Training set consisted of 33% of the data and validation set consisted of 67% of the entire data. Note that the training set was not used in comparison of the simulations and experiments results in the Results and Discussion section of this paper (only validation set was used). More information on the maximum likelihood least squares fitting approach can be found in [107].

To integrate Eq. 2, the effective saturation should be expressed as a function of capillary suction (i.e., $\Theta = \Theta(h)$). Different models for $\Theta = \Theta(h)$ have been developed [102, 26]. The model proposed by van Genuchten [203, 204] is used in this study and is shown in Eq. 5.4

$$\Theta = \frac{1}{1 + (\alpha h)^n}, m = 1 - \frac{1}{n} \quad (5.4)$$

where $\alpha$ and $n$ are fitting parameters ($\alpha$, inversely proportional to the mean pore diameter ($mm^{-1}$) and $n$ (non-dimensional) is a curve-shape parameter). These fitting parameters are obtained by fitting Eq. 5.4 to experimentally obtained water retention curves using the least squares method [107]. In the case of cement-based materials, instead of water retention, $\Theta = \Theta(h)$, it is more common to measure the sorption isotherm of material (i.e., $\Theta = \Theta(RH)$, RH = relative humidity). The sorption isotherm can then be converted to retention curve using Kelvin-Laplace Equation (Eq. 5.5) [155, 108, 64, 21]:

$$h = \ln(RH) \frac{RT}{MG} \quad (5.5)$$

where $R$ (J.K$^{-1}$ mol$^{-1}$) is universal gas constant, $T$ (K) is the temperature, $M$ (kg/mol) is the molecular mass, and $g$ is the gravitational constant (9.81 m/s$^2$). We would like to point out here that an alternate form of Eq. 5.5 may be written in terms of surface tension, $\gamma$ (N/m), and capillary radius $r$ (m): $\ln(RH) = \frac{M}{\rho RT} \frac{2\gamma}{r}$, where $\rho$ (kg/m$^3$) is the density of water. This form is useful when the capillary radius is required.

### 5.3.3 Material model with moisture retention hysteresis

The procedure for determining moisture retention curves described above is valid for both drying and rewetting of the material. However, moisture retention curves obtained using an initially-saturated specimen do not consider the effects of hysteresis. While the assumption that the parameter $n$ remains unchanged during hysteresis has been shown to be an acceptable approximation [141, 101], the re-wetting hydraulic parameters $\alpha_w$ and $\theta_w$ should be separately determined for the hysteresis model.

Since obtaining adsorption isotherms generally requires significant experimental time due to diffusion and dissolution of trapped air, which may be impractical in many cases, we use an analytical expression for $\alpha_w$ and experimental data to determine $\theta_w$. In addition, we approximate
that the saturated hydraulic conductivity, $K_s$, and tortuosity-pore connectivity parameter, $I$, remain the same in both drying and re-wetting. Such approximations regarding the parameters $K_s$ and $I$ may result in overestimation of initial sorptivity, as the magnitude of saturated hydraulic conductivity often decreases after drying [174, 16, 122]. Unfortunately, history-dependent data for $K_s$ and $I$ in damaged cementitious material are nonexistent.

The re-wetting parameter $\alpha^w$ is physically related to the mean pore diameter after the first drying cycle. In porous materials, $\alpha^w$ is generally larger than in the first drying case (i.e. $\alpha^w > \alpha$), which is largely due to air-entry into the pore system. $\alpha^w = 2\alpha$ is commonly accepted as a first approximation [101] and is used herein.

The saturated moisture content of a re-wetting material is less than that of the initial saturation (i.e. $\theta_s > \theta^w_s$) due to the presence of air in large pores. Here we determine $\theta^w_s$ using experimental absorption data (from the sorption test, discussed in the Materials and Methods section). The sorption measurements beyond 90 days show negligible mass gain of the samples and, as such, it is assumed here that $\theta^w_s$ is equal to the saturated moisture content after 90 days of rewetting. While this rough approximation may lead to slight underestimation of the saturated moisture content of the rewetting material, it was found to be suitable for the hysteresis model presented. Ingress is defined as, $i = \frac{V_w}{A}$, where $V_w$ (mm$^3$) and $A$ (mm$^2$) are the volume of absorbed water and cross-sectional area of the absorbing specimen, respectively. If assumed to be in a completely saturated state, we can approximate $i = \frac{V_w}{A} = \frac{\theta^w_s V_s}{A}$, where $V_s$ is the volume of the specimen. By rearranging, we obtain the expression for the re-wetting volumetric saturated moisture content: $\theta^w_s = \frac{i A}{V_s}$.

The use of hydraulic parameters $\theta^w_s$ and $\alpha^w$ have significant implications on the moisture retention curves of the re-wetting material. To illustrate this, Figure 5.1 shows drying and rewetting moisture retention curves for concrete and mortar with the highest degrees of damage. We note that the initial drying curves shown in Figure 5.1 were determined by using Eq. 5.5 to convert $RH$ to $h$ from the desorption isotherms. Then the complete curve was plotted by determining the fitting parameters in Eq. 5.4 using the experimental data. The rewetting curves were then determined for the same materials using $\alpha^w = 2\alpha$ and $\theta^w_s = \frac{i A}{V_s}$.

5.3.4 Numerical Simulation and Experimental Corroboration

In this work, a commercially available Finite Element Software, HYDRUS 3D, was used [215]. The sorption test was simulated by modeling water sorption in a 100 mm x 25 mm cylinder. Zero-flux boundary conditions were applied to all surfaces except the bottom surface were the sample was in contact with water. The boundary condition at the bottom surface was saturated boundary condition. Uniform initial moisture content, $\theta_i$, were considered in this study; values for $\theta_i$ were experimentally obtained and are tabulated in the results section. It should be noted
Figure 5.1: Drying and rewetting moisture retention curves; (a) concrete (C47) with a high degree of damage (47%) and (b) mortar (M48) with high degree of damage (48%).

that the specimens used for sorption measurement were conditioned according to ASTM C1585, which does not guarantee a uniform initial moisture distribution. Achieving a uniform initial moisture distribution requires long-term conditioning, on the order of a few years [34]. Therefore, in this work the simplifying assumption of uniform initial moisture condition was considered. The discussion of the effect of conditioning can be found in [34].

Finite element modeling consisted of tetrahedron elements with a maximum dimension of 1.0 mm. The finite element model was solved in terms of moisture content. The material parameters determined using the methods discussed in Section 5.3.2 and 5.3.3 (reported in Table 5.2, Section 5.5.2) were input directly into the HYDRUS 3D.

5.4 Materials and Methods

5.4.1 Materials

Both mortar and concrete were used. Table 5.1 reports the mixture proportions for concrete and mortar. It should be noted that the mixture proportions reported in Table 5.1 are for saturated surface dry (SSD) fine and coarse aggregates. No air entraining agent was used. Entrapped air is taken in this work as a part of the open porosity. The open porosity of the hardened material can be taken as the volumetric moisture content at saturation as discussed in [81]. In this work, the volumetric moisture content at saturation was experimentally measured. For both materials, cylindrical samples with dimensions 200 mm x 100 mm (100 mm diameter) were cast. All specimens were cut into disks (25 mm x 100 mm) after 24 hours of sealed curing and then were stored for 12 months in lime saturated water. This was done to ensure uniform
saturation, minimize leaching, and to uniformly mature the specimens. More detailed discussion of the benefits of lime-saturated curing may be found in [184].

Table 5.1: Mix proportions of concrete and mortar

<table>
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<tr>
<th>Proportions</th>
<th>Concrete</th>
<th>Mortar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement(^a) (kg/m(^3))</td>
<td>261</td>
<td>609</td>
</tr>
<tr>
<td>Fly Ash (kg/m(^3))</td>
<td>83(^b)</td>
<td>–</td>
</tr>
<tr>
<td>Water (kg/m(^3))</td>
<td>132.5</td>
<td>256</td>
</tr>
<tr>
<td>Coarse Aggregate(^c) (kg/m(^3))</td>
<td>1073</td>
<td>0</td>
</tr>
<tr>
<td>Fine Aggregate(^d) (kg/m(^3))</td>
<td>747</td>
<td>1466</td>
</tr>
<tr>
<td>Water Reducer (kg/m(^3))</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>w/c</td>
<td>0.50</td>
<td>0.42</td>
</tr>
</tbody>
</table>

\(^a\) Ordinary Type I portland cement
\(^b\) 24% replacement by mass of cement
\(^c\) Crushed limestone (MSA = 19 mm)
\(^d\) Natural river sand, (FM = 2.67)
\(^e\) Mixture proportions are for saturated surface dry (SSD) fine and coarse aggregates
5.4.2 Freeze-Thaw Loading

Specimens were subjected to freeze-thaw loading in an air-cooled chamber to induce different degrees of damage following the procedure in Li et al. [109]. To keep the specimens saturated during testing, they were wrapped in water-saturated cloth and sealed in a thin plastic sheet. To obtain a similar degree of damage in mortar and concrete, different temperature profiles and number of cycles were used in each material. In concrete, the freeze-thaw cycle lasted 12 hours. Each cycle consisted of a 2-hour cooling period from 20 to -23$^\circ$C, a 4-hour rest period at -23$^\circ$C, a 2-hour heating period from -23 to 20$^\circ$C, and a 4-hour rest period at 20$^\circ$C. A maximum of 5 cycles were used in concrete.

In freeze-thaw loading of mortar, each cycle was 4 hours, including a cooling period from 21 to -35$^\circ$C and a heating period to 21$^\circ$C. A maximum of 25 cycles was used in mortar. Concrete specimens with five different degrees of damage (10, 21, 29, 36, and 47%) and mortar specimens with three different degrees of damage (18, 30, and 48%) were prepared. The method of quantifying damages is provided in the next section.

5.4.3 Quantifying Damage due to Freeze-Thaw

The degree of damage after a given number of freeze-thaw cycles was quantified using the change in dynamic elastic modulus using active acoustic emission similar to [165, 70, 109]. Active acoustic emission describes a method in which a series of acoustic pulse (four discrete pulses in this work) is sent by an acoustic emission sensor and is captured by another sensor (pitch-catch). Then, the order of sending and receiving the pulse is switched between the two sensors. The signal transmission time is measured for all the pulses and the average value is reported (average of eight measurements). Acoustic emission sensors with a peak frequency of 375 kHz were used. Sensors were installed on opposite sides of 25 mm thick disk specimens, the perimeter of which were slightly trimmed tangent to the edge to properly install the sensors. Disk specimens were then placed on a layer of acoustic mat on a rigid, stainless steel frame. Damage was estimated based on the wave travel time in undamaged and damaged specimens and calculating the relative elastic modulus:

\[
D = 1 - \frac{E_t}{E_0} = 1 - \left(\frac{t_0}{t_t}\right)^2
\]

(5.6)

where $E_t$ is the dynamic elastic modulus after freeze-thaw damage, $E_0$ is the initial dynamic elastic modulus (before freeze-thaw damage), $t_t$ is the signal transmission time after freeze-thaw, and $t_0$ is the signal transmission time before freeze-thaw damage. In Eq. 5.6, the change in density of the damaged material is considered negligible.
5.4.4 Desorption Isotherm

Concrete

Specimens, with different degrees of damage, were conditioned at five relative humidities (50%, 65%, 75.3%, 85.1%, and 93.6%). The concrete specimens had an average mass of 52.5 g and an average thickness of 5.64 mm. The specimens were cut from the center of cylinder using a precision tile wet-saw before freeze-thaw loading. The RH values were selected from standard salt solutions: NaCl₂ (75.3% RH), KCl (85.1% RH), and KNO₃ (93.6% RH) following the work by [34], except for the 50% and 65% RH where environmental chambers were used to fill intermediate RH values. Specimens were conditioned using saturated salt solutions, except for the 50% and 65% RH where environmental chambers were used to fill intermediate RH values. Equilibrium at a given relative humidity was defined as a change in mass less than 1.0 mg in one month. A total of three replicate specimens were used for each degree of damage (a total of 108 samples for all degrees of damage and RH). The total time required to reach equilibrium for all the samples and complete all measurements was approximately 9 months. Note that measurements were performed simultaneously. It was found that the time to reach equilibrium (regardless of the RH increment) was shorter for materials with higher degrees of damage. This may be, in part, attributed to higher porosity and higher pore connectivity of materials with a higher degrees of damage.

Mortar

To measure desorption isotherm of mortar specimens with different degrees of damage, an automated sorption analyzer was utilized. Small samples (0.5-1.5 mm thick, weighing 50-100 mg) were used; these samples were cut with a precision Scanning Electron Microscope wet-saw operating at 120 rpm with 5g of added mass to ensure the samples were not damaged during cutting. We note that this careful procedure was especially important at high degrees of damage, when the material had a degraded strength. These samples, with an average dimension of approximately 1 mm well represented the bulk material in absorption simulations. A discussion of the effect of sample size is provided in the Results and Discussion Section. In the sorption analyzer, mass of the specimens were monitored while the relative humidity was sequentially dropped from 97.5% to 0% RH, with a 5% RH decrease between each successive step after reaching equilibrium. Equilibrium was defined as a mass change less than 0.001 mg within 15 minutes. This criterion was previously developed, tested, and validated in the comprehensive studies by [211, 34, 156].
5.4.5 Saturated Hydraulic Conductivity

The saturated hydraulic conductivity ($K_s$) measurements were performed using an in-house developed equipment shown in Figure 5.2. The details of the saturated hydraulic conductivity test can be found in [70]). Measurements were performed on initially saturated 25 mm thick disks. It is important to note that the specimens were never dried. A total of three replicates were used for concrete and a total of four replicates were used for mortar at each degree of damage.

![Figure 5.2: In-house developed equipment to measure saturated hydraulic conductivity; (a) photograph of equipment, (b) schematic of equipment implementation](image-url)
5.4.6 Water Sorption

Sorptivity test describes the water absorption by capillary suction. To measure the amount of absorbed water by the specimen, the specimen was placed in contact with water and the mass of the specimen is monitored over time. In this work, water absorption was carried out following ASTM C1585; however, experiments were carried out up to 90 days rather than the specified 7 day testing duration. The specimen conditioning according to ASTM C1585 requires drying of the specimen at 50°C. It is assumed that this drying did not induce further damage, since no large temperature gradients are present across the sample in this procedure. Prior to the experiments, the perimeter of the specimens was sealed using epoxy. To avoid contamination of circular cross-sectional surfaces with epoxy, they were covered with pieces of paper during the application of epoxy.

5.4.7 Scanning Electron Microscope

Specimens analyzed by a scanning electron microscope were oven dried at 50°C for 48 hours. To minimize cracking that may result from polishing and cutting, the specimens were penetrated with ultralow viscosity epoxy under a high-pressure vacuum pump (0.015 mm Hg). The epoxy-conditioned specimens were then oven cured at 50°C for 10 hours followed by cutting and polishing with carbide sandpaper. The polishing consisted of sanding with low-grit to progressively higher grit sandpaper (60, 120, 240, 320, 400, 600, 800 and 1,200 grit) and half-micron diamond suspension. The backscattered mode was used for SEM imaging with pressure and accelerating voltage of 30 Pa and 20 kV, respectively.

5.5 Results and Discussion

5.5.1 Freeze-Thaw Damage Visualization and Detection

SEM images for six degrees of damage are shown in Figure 5.3, the left column shows SEM images of concrete and the right column shows SEM images of mortar. These images are provided to visualize damage in the materials. In the images shown, it is clear that freeze-thaw damage is distributed across the cement paste phase, although some fractures are observed along the aggregate boundaries. As damage increases, the fractures become interconnected and wider in both mortar and concrete. In Figure 5.3, fracture widths, in all degrees of damage, are below 25 µm. However, pore sizes, for cement paste in general, range from nanometers to approximately 0.05 µm [119]. The mortar specimen sizes used in this work for obtaining desorption isotherms are, at a minimum 100-2,500 times larger in dimension than the distributed pore or fracture systems. Consistent with representative volume element (RVE) size discussed by Nemat-Nasser.
and Hori [138], the specimen sizes used for desorption isotherms of mortar are much larger than the microstructure, and therefore, well-represent bulk material properties. By the same argument, the use of desorption analyzer was deemed inappropriate for measuring desorption isotherms of concrete due to the large aggregate sizes. Indeed, the concrete specimens tested here had aggregates with a maximum size of 19 mm, resulting in a much larger RVE size than mortar.

The damage shown in the material depicted in Figure 5.3 was quantified using the change in elastic properties using active acoustic emission methods. In Figure 5.4, the measured degrees of damage using active emission for both mortar and concrete are reported. The error bars in Figure 5.4 represent standard deviation. The degree of damage in mortar and concrete increases linearly with the number of freeze-thaw cycles.
Figure 5.3: In-house developed equipment to measure saturated hydraulic conductivity; (a) photograph of equipment, (b) schematic of equipment implementation.
Figure 5.4: Degree of Damage, $D (%)$, based on the reduction of elastic modulus using acoustic emission; (a) concrete, (b) mortar.

5.5.2 Material Parameters

Figures 5.5a and 5.5b show the measured desorption isotherms for mortar and concrete specimens, respectively. The desorption isotherms of mortar have a higher number of data points and a wider range of RH values, as compared to that of concrete, since they were measured using an automated sorption analyzer.

Figure 5.5: Desorption isotherm of specimens with different degrees of damage; (a) mortar, (b) concrete. M and C denote mortar and concrete, respectively, and the number following these letters indicate the degree of damage (%).
Table 5.2: Saturated hydraulic conductivity, saturation water content, and van Genuchten model parameters for mortar and concrete specimens

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Damage</th>
<th>$K_s$ [$10^{-4} \text{ mm hr}^{-1}$]</th>
<th>$\alpha$</th>
<th>$\alpha_w$ [$10^{-2} \frac{1}{\text{mm}}$]</th>
<th>$n$</th>
<th>$I$</th>
<th>$\theta_i$</th>
<th>$\theta_s$</th>
<th>$\theta_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0</td>
<td>0</td>
<td>0.3</td>
<td>1.2</td>
<td>2.4</td>
<td>2.06</td>
<td>-9.0</td>
<td>0.03</td>
<td>0.14</td>
<td>0.10</td>
</tr>
<tr>
<td>M18</td>
<td>18</td>
<td>5.9</td>
<td>1.8</td>
<td>3.6</td>
<td>1.75</td>
<td>-8.0</td>
<td>0.01</td>
<td>0.15</td>
<td>0.14</td>
</tr>
<tr>
<td>M30</td>
<td>30</td>
<td>19.4</td>
<td>3.3</td>
<td>6.6</td>
<td>1.52</td>
<td>-8.0</td>
<td>0.02</td>
<td>0.17</td>
<td>0.15</td>
</tr>
<tr>
<td>M48</td>
<td>48</td>
<td>34.1</td>
<td>3.4</td>
<td>6.8</td>
<td>1.81</td>
<td>-8.0</td>
<td>0.01</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>C0</td>
<td>0</td>
<td>1.4</td>
<td>6.4</td>
<td>13.0</td>
<td>2.26</td>
<td>-7.0</td>
<td>0.03</td>
<td>0.15</td>
<td>0.11</td>
</tr>
<tr>
<td>C10</td>
<td>10</td>
<td>7.0</td>
<td>4.9</td>
<td>9.8</td>
<td>2.45</td>
<td>-7.0</td>
<td>0.03</td>
<td>0.15</td>
<td>0.11</td>
</tr>
<tr>
<td>C21</td>
<td>21</td>
<td>14.0</td>
<td>4.6</td>
<td>9.2</td>
<td>2.47</td>
<td>-7.0</td>
<td>0.04</td>
<td>0.16</td>
<td>0.11</td>
</tr>
<tr>
<td>C29</td>
<td>29</td>
<td>26.0</td>
<td>4.6</td>
<td>9.2</td>
<td>2.48</td>
<td>-6.0</td>
<td>0.03</td>
<td>0.17</td>
<td>0.12</td>
</tr>
<tr>
<td>C36</td>
<td>36</td>
<td>56.0</td>
<td>4.1</td>
<td>8.2</td>
<td>2.64</td>
<td>-5.0</td>
<td>0.03</td>
<td>0.18</td>
<td>0.13</td>
</tr>
<tr>
<td>C47</td>
<td>47</td>
<td>131.0</td>
<td>4.3</td>
<td>8.6</td>
<td>2.58</td>
<td>-5.0</td>
<td>0.03</td>
<td>0.19</td>
<td>0.14</td>
</tr>
</tbody>
</table>

For both materials the isotherms shift upward with increased damage, indicating damage increases porosity over a wide range [70]. The van Genuchten model (Eq. 5.4) was fit to these isotherms, after converting them to water retention curves using Eq. 5.55. The van Genuchten model parameters for mortar and concrete are reported in Tables 2 and 3 respectively. The values for saturated hydraulic conductivity ($K_s$), saturated moisture content ($\theta_s$), empirical parameter $I$, and the rewetting parameters ($\theta_w$ and $\alpha_w$) are also reported in Tables 5.2. In Table 5.2 C and M stand for concrete and mortar respectively, and the number following these letters indicates the degree of damage.

We would like to point out here that while Mualem [135] proposed the parameter $I$ to account for tortuosity and pore connectivity, such a physical interpretation may be only meaningful if $I > 0$ in the classical model of unsaturated hydraulic conductivity [53]. In this study, using the approach described in Section 2.2, satisfactory results were found for negative values similar to the works in [181, 160, 177, 228, 183].

In addition to $I$, the saturated hydraulic conductivity ($K_s$) and open porosity ($\theta_s$) have significant effects on the sorptive behavior of cement-based materials. In particular, $K_s$ considerably influences initial sorptivity. $K_s$ is shown in Figure 5.6a to increase with the degree of damage in both mortar and concrete. Figure 5.6b shows that $\theta_s$ increases with damage, similar to the increase of porosity observed in desorption isotherms. $\theta_s$ (or $\theta_w$ in the case of hysteresis) largely influences the final magnitude of moisture ingress and the duration of initial absorption. While the values of open porosity in mortar and concrete are similar in magnitude, $K_s$ of concrete is significantly higher than that of mortar, especially at higher degrees of damage. This indicates that the open porosity (pores and fractures) are better connected in concrete as...
compared to mortar.

Figure 5.6: Effect of damage, D (%), on (a) saturated hydraulic conductivity and, (b) open porosity, $\theta_s$, in mortar and concrete.

5.5.3 Simulation of Unsaturated Moisture Transport in Mortar

Results of the experimental measurements and numerical simulations of water absorption of mortar with different degrees of damage are compared in Figure 5.7. Simulations of water absorption using the material model without hysteresis (from the desorption isotherm) and the proposed material model including hysteresis are included. The results are presented as volume of water (mm$^3$) absorbed per water absorbing surface (mm$^2$) of the sample versus square root of time (day$^{1/2}$). The results were compared for the first 90 days. Note that for each degree of damage, simulation results are compared with experimental results from two samples.
Figure 5.7: Experimental and numerical sorption results for mortar specimens with different degrees of damage; a) D = 0%, b) D = 18%, c) D = 30%, d) D = 48%.
In Figure 5.7, for all degrees of damage, the results of simulations of water absorption in mortar compare well with experimental results at early stages of water absorption. In simulations where hysteresis is considered, early-stage results more closely match experimental results. The slope of the first linear portion of the experimental and numerical results, initial sorptivity, is calculated and plotted as a function of degree of damage in Figure 5.8. Figure 5.8 confirms that the results of simulation for the initial stages of water absorption agree well with experimental results, particularly in simulations where hysteresis is considered.

![Figure 5.8: Comparison of experimentally and numerically obtained initial sorptivity, $S_i$, of mortar as a function of damage.](image)

In Figure 5.7, at later stages of water absorption, simulation results deviate from the experimental results. The deviation increases with damage level. As the damage increases, a sharp knee point appears in both experimental and numerical results. There is, however, a distinct difference between the numerical and experimental results after the knee point. In simulated results the sharp transition marks the transition from unsaturated to saturated state of the sample while in experimental results the specimen continues to absorb water after the knee point. In experimental results, the knee point marks transition from capillary suction to air diffusion and dissolution mechanism of water absorption [70, 71]. Since Richards Equation does not account for air diffusion and dissolution mechanisms, in simulation results (Figure 5.7), the specimen continues to absorb water until saturation [109]. However, in experimental results, the specimen continues to absorb water after the knee point, largely due
to the effects of air diffusion and dissolution mechanisms.

5.5.4 Simulation of Unsaturated Moisture Transport in Concrete

Results of the experimental measurements and numerical simulation of water absorption in concrete with different degrees of damage are compared in Figure 5.9. Simulation results considering hysteresis are also reported. Similar to the results for mortar specimens, the results are compared for the first 90 days. Note that for each degree of damage, simulation results are compared with experimental results from two samples.

The results in Figure 5.9 are similar to the results presented in Figure 7. At early stages of water absorption, the simulation and experimental results agree well while they diverge at later stages of water absorption. Simulations considering moisture hysteresis are shown to more closely match experimental results in both late- and early-stages of moisture. This is largely due to the improved estimation (relative to using drying data) of saturated moisture content after drying.
Figure 5.9: Experimental and numerical sorption results for concrete specimens with different degrees of damage; a) D = 0%, b) D = 10%, c) D = 21%, d) D = 29%, e) D = 36%, f) D = 47%.
Figure 5.10, similar to Figure 5.8, compares the initial sorptivity calculated from experimental and numerical results. Again, Figure 10 confirms that the results of simulation for the initial stages of water absorption agree well with experimental results. Considering the effect of hysteresis in the simulations significantly improves the estimation of initial sorptivity at higher degrees of damage.

Figure 5.10: Comparison of experimentally and numerically obtained initial sorptivity, $S_i$, of concrete as a function of damage.
5.5.5 Discussion of Unsaturated Moisture Absorption Modeling Using the Classical Isothermal Model

Simulation of moisture ingress using Richards Equation only describes the physics of capillary suction. For cementitious material with distributed damage, the accuracy of simulation results is highly dependent on the experimentally obtained isotherms and hydraulic parameters. In particular, the value of saturated hydraulic conductivity and open porosity significantly affect the simulation results. The advantages of using the simulation techniques presented in this paper are (i) the material parameters are directly measured using well-researched and well-developed experimental techniques, (ii) simulation of moisture absorption using Richards Equation requires relatively few modeling parameters, and (iii) the material model considering hysteresis does not require the adsorption isotherm the acquisition of which may require considerable experimental time.

However, the simulation techniques presented herein have some limitations. The simple moisture hysteresis model does induce some uncertainty, since modeling parameters do not originate from the adsorption isotherm. Moreover, in the modeling approach used here, homogenized material parameters are used which account for the overall contribution of matrix and fractures, and therefore, this model neglects direct simulation of matrix-fracture moisture transfer. While early-stage simulation results were generally satisfactory, neglecting matrix-fracture interaction and air diffusion/dissolution lead to the divergence of simulation results from experimental results in late-stages of water absorption where hysteresis is not considered. To improve simulation results at late-stages of water absorption, especially at high levels of saturation and damage, the feasibility of advanced models such as dual-permeability or dual-porosity should be studied. Furthermore, models for air-diffusion and dissolution may improve simulations of late-stage moisture absorption.

5.6 Conclusion

In this work, a classical isothermal unsaturated moisture transport model was used to simulate moisture ingress in mortar and concrete with a wide range of damage. In the material model where hysteresis was not considered, material parameters were obtained from experimental measurements. For the material model accounting for hysteresis, material parameters were developed based off experimental and analytical means. The results indicate that, for all levels of damage, the classical isothermal unsaturated moisture transport model well simulates the early stages of moisture ingress in mortar and concrete where capillary suction is the underlying mechanism. At later stages where air diffusion and dissolution mechanisms as well as matrix-fracture interaction play a more significant role, the results of simulations excluding the effects
of hysteresis deviate from experimental measurements. In contrast, results of late-stage water absorption in simulations considering hysteresis more closely match experimental results. The use of more advanced material models might be necessary to obtain more accurate results at later stages of water absorption.
Chapter 6

Can the Dual-Permeability Model be Used to Simulate Unsaturated Moisture Flow in Damaged Mortar and Concrete?

6.1 Abstract

Moisture is one of the main contributors to the majority of the deterioration processes that occur in reinforced concrete structures. Moisture ingress, very often, occurs in unsaturated concrete structures. In addition, some level of damage is usually present in structural concrete, for example, due to mechanical or environmental loading. Therefore, for a more accurate service life prediction of reinforced concrete structures, methods for modeling unsaturated flow in damaged cement-based materials are needed. Previous works have shown that the classical isothermal unsaturated flow modeling fails to adequately describe the long-term moisture ingress in damaged cement-based materials since this method of modeling neglects air diffusion/dissolution and does not explicitly account for the matrix-fracture interaction.

In the present paper we (i) investigate whether the dual-permeability modeling approach can be used to more accurately model unsaturated moisture flow in damaged cement-based materials especially at later stages of moisture ingress, (ii) propose methods of obtaining the transport modeling parameters of the fracture phase that cannot be directly measured, and (iii) propose a model for moisture transfer coefficient across matrix-fracture interface and discuss the effect of this parameter on the results. We compare the results of dual-permeability and classical isothermal modeling against experimental results for damaged mortar and concrete.
Finally, we discuss modeling challenges that may arise in applications of the dual-permeability model in simulating unsaturated moisture flow in damaged mortar and concrete.

6.2 Introduction

The deterioration rate of concrete structures is strongly influenced by the rate of moisture ingress [56, 178, 153, 33, 45]. The rate of moisture ingress, in turn, is affected by the presence of cracks and distributed damage [70, 4]. The significant effect of distributed damage on moisture ingress in concrete has been shown in previous experimental research. Samaha and Hover [175] observed that chloride migration, measured by the Rapid Chloride Penetration Test, in concrete specimens loaded above 75% of their compressive strengths increased by 20%. Yang et al. [226] showed that the cumulative moisture absorption increased linearly with increasing damage. Auroy et al. [13] found that distributed microcracking due to carbonation shrinkage generally increased the unsaturated effective permeability in cement pastes. Wu et al. [224] showed that the size of microcracks had a significant effect on the moisture transport mechanisms in concrete. Ghasemzadeh and Pour-Ghaz [70] and Ghasemzadeh et al. [71] showed that the effect of distributed damage on mass transport in concrete depends on the mechanism of transport, and therefore, measurement techniques that are not based on the same mechanisms show the effect of damage differently.

In addition to the experimental works, researchers have used numerical methods to study unsaturated moisture transport in cement-based materials. Unsaturated moisture flow is commonly modeled using classical Richards’ Equation [166] since capillary suction is the prominent mechanism of moisture transport in cement-based materials [33, 14, 80, 123]. While analytical methods of solving the classical Richards’ Equation for simple geometries and boundary conditions exist [30, 145], arbitrary geometry and boundary conditions require the use of numerical methods such as the Finite Element Method [154]. Examples of recent numerical studies of unsaturated moisture transport in cementitious material include [50, 90, 161, 89, 159, 74, 176, 139, 155, 14]. These studies have provided significant insights and enhanced our understanding of the unsaturated transport in cement-based materials in the absence of damage. However, simulation of unsaturated moisture transport in cementitious material with distributed damage is rarely investigated. Recently, Smyl et al. [187] numerically simulated unsaturated moisture transport in damaged and undamaged mortar and concrete using the classical isothermal unsaturated moisture transport. While their results showed a good agreement with experimental data at early stages, simulation results in the late stages of moisture absorption diverged from the experimental results. This suggests that to more accurately simulate long-term moisture ingress more advanced models are needed.

In this paper, (i) we investigate whether a dual-permeability modeling approach can be used
to more accurately model unsaturated moisture flow in damaged cement-based materials, (ii) we propose methods of obtaining the transport modeling parameters of the fracture phase that cannot be directly measured, and (iii) we propose a model for moisture transfer coefficient across matrix-fracture interface and discuss the effect of this parameter on the results. We compare the results of dual-permeability and classical isothermal modeling against experimental results for damaged mortar and concrete.

In the following, the numerical methods used in this paper are fully described. Then, the material models and methods of obtaining matrix and fracture parameters are presented. This is followed by a description of materials and experimental methods, and finally, results are discussed.

### 6.3 Numerical Methods: Dual-Permeability and Classical Models

In the dual-permeability model, unsaturated moisture flow within the "matrix" and "fracture" domains is considered and it is assumed that the moisture can be transported in the matrix, in the fractures, and between the matrix and fractures. Figure 6.1 is a schematic of the material domain, consisting of matrix and fracture domains. In the absence of the fracture domain, the dual-permeability model reduces to the classical unsaturated flow model.

![Figure 6.1: Schematic of a dual-permeability material with arbitrary capillary pressure conditions](image-url)
The dual-permeability model [69] is described by Eqs. 6.1 and 6.2

\[
\frac{d\theta_m}{dt} = \frac{d}{dx_i} \left[ K_m(h_m) \left( \frac{dh_m}{dx_j} + \delta_{ij} \right) \right] - S_m - \frac{\Gamma}{1 - v_f} \tag{6.1}
\]

\[
\frac{d\theta_f}{dt} = \frac{d}{dx_i} \left[ K_f(h_f) \left( \frac{dh_f}{dx_j} + \delta_{ij} \right) \right] - S_f - \frac{\Gamma}{v_f} \tag{6.2}
\]

where subscripts "f" and "m" denote the fracture and matrix phases. We define the fracture phase as the total volume fraction of the cracks and the matrix phase as the total volume fraction of otherwise undamaged material. Moreover, \( x_i[mm] \) is the spatial coordinate \((i = 1, 2, 3 \text{ for three dimensional space);} \)
\( K_m = K_m(h_m)[mm/hour] \) and \( K_f = K_f(h_f)[mm/hour] \) are the unsaturated hydraulic conductivities; \( \theta_f \) and \( \theta_m[mm^3/mm^3] \) are the volumetric moisture contents; \( h_f \) and \( h_m[mm] \) are the pressure heads; \( S_f \) and \( S_m[hr^{-1}] \) are the sink/source terms; \( v_f[mm^3/mm^3] \) is the volume fraction of the fractures; \( \delta_{ij} \) is the Kronecker Delta symbol which accounts for the gravitational effect [155], and \( \Gamma[hr^{-1}] \) is the moisture transfer rate between the matrix and the fracture phases. It is emphasized here that Equations 6.1 and 6.2 presume incompressible phases, since divergence of velocity is not considered [196].

In this study, the authors use \( \Gamma = \beta_w(h_f - h_m) \), a relation commonly used in soil and rock mechanics [185], where \( \beta_w[mm^{-1}hr^{-1}] \) is the first-order rate coefficient, i.e, the compliance of a material to transfer moisture between the matrix and fractures. We present a new model for \( \beta_w \) in the next section.

To the authors’ knowledge (also noted in [219]), no implementation of Eqs. 6.1 and 6.2 exists for damaged cementitious materials and cementitious materials in general, in the literature. We provide herein our physical interpretation of Eqs. 6.1 and 6.2 for cement-based materials.

The coupling of Eqs. 6.1 and 6.2 can be used to model multiple processes. For example, Eq. 6.2 can be used to describe air void phase instead of fracture phase where in that case \( v_f \) represents the volume fraction of air voids. Similarly, Eq. 6.2 can be used to describe the behavior of internal water reservoirs such as lightweight aggregate (LWA) or superabsorbent polymers (SAP) where again in that case, \( v_f \) represents the volume of available water from the reservoirs. Alternatively, \( S_f \) and \( S_m \), can be used to represent addition or removal of moisture in the material volume, for example due to hydration or internal curing using LWA or SAP. In modeling internal water reservoirs, the difference between the two approach is that the former can explicitly account for the desorption and absorption behavior of internal water reservoirs, whereas, using sink/source terms (i.e., \( S_f \) and \( S_m \)) does not allow for such an explicit modeling. In this work, we consider \( S_m = S_f = 0 \) since there are no sources of internal moisture, such as LWA and SAP, in the mixture and the material considered in this work are mature (cured in saturated condition for over 12 month), and therefore, the rate of hydration is negligible.

It is important to note that in unsaturated systems or when the source terms (\( S_f \) and \( S_m \))
are non-zero, models based on conservation of mass more accurately describe the system since they account for volume change during condensation and evaporation. The choice of the model in the present work, therefore, adds additional uncertainties to the results.

In the context of modeling moisture flow in damaged cement-based materials, while Eqs. 6.1 and 6.2 describe matrix and fracture phases respectively, there is an overlap between the two phases. Therefore, each of the Eqs. 6.1 and 6.2 carry some information about the other phase. This is because, matrix phase has some amount of large pores, e.g., due to entrapped or entrained air, that have a similar desorption/absorption behavior to that of fractures, and fracture phase has some amount of very fine cracks that have desorption/absorption behavior similar to that pores in the matrix phase. The overlap in modeling the two phases with Eqs. 6.1 and 6.2, we expect, to increase when (i) the matrix has a wider pore distribution and especially when the matrix phase has larger fraction of large pores, and (ii) when the degree of damage increases and therefore fracture phase has a wider size distribution and especially when the fracture phase has a larger fraction of smaller fractures.

The overlap in modeling the matrix and fracture phases can increase even more depending on the method used to obtain their transport modeling parameters. Especially, it is not possible to directly measure the properties of fracture phase, and using some assumption and models, the properties of fracture phase need to be estimated indirectly. Depending on the nature of these assumptions and models, the overlap between the properties of the matrix and fracture changes. We highlighted these points since they need to be considered in the interpretation of the results.

Finally, we would like to mention that in the absence of the fracture phase ($v_f = 0$ and $\Gamma = 0$), Eqs. 6.1 and 6.2 reduce to the classical model for unsaturated moisture transport in porous media (Richards Equation [166]) shown by Eq. 6.3:

$$\frac{d\theta}{dt} = \frac{1}{d} \left[ K(h) \left( \frac{dh}{dx_j} + \delta_{ij} \right) \right]$$  

(6.3)

where $K = K(h)[mm/hour]$ is the unsaturated hydraulic conductivity of the medium, $\theta[mm^3/mm^3]$ is the volumetric moisture content, $h[mm]$ is the pressure head. We would like to highlight that the classical model does not explicitly account for the matrix-fracture interaction and homogenized hydraulic properties for the entire domain is used in the classical model, effectively using an overall hydraulic property for the entire domain.
6.4 Material parameters and models

6.4.1 Unsaturated hydraulic conductivity

The hydraulic conductivity of an unsaturated fractured porous medium is commonly expressed using three different methods: (1) a homogenized hydraulic conductivity is considered for the entire domain averaging hydraulic conductivity of the fracture and matrix phases, (2) hydraulic conductivity of the fractures and matrix are expressed separately and their interaction is ignored, and (3) hydraulic conductivity of fractures and matrix are expressed separately and their interaction is modeled. The last method is the most general material model and most accurately describes the physics of unsaturated dual-phase fractured porous media [43, 213, 69]. However, systematic methods of modeling the fracture domain, matrix domain, and their interaction are not well established for the third method. For a review of material models incorporating related concepts in saturated fractured porous media, we refer the reader to [54].

Unsaturated hydraulic conductivity of the matrix and fracture domain ($K_m$ and $K_f$, respectively) are a function of pressure head (i.e., $K_m = K_m(h_m)$ and $K_f = K_f(h_f)$). Unsaturated hydraulic conductivity measurements are very difficult and time consuming, especially for cement-based materials due to their fine pore size distribution. Therefore, unsaturated hydraulic conductivity is commonly expressed as a product of the saturated hydraulic conductivity ($K_{s,f}$ and $K_{s,m}$) and relative hydraulic conductivities ($K_{r,f}$ and $K_{r,m}$), such that $K_f = K_{r,f}K_{s,f}$ and $K_m = K_{r,m}K_{s,m}$ where subscripts "f" and "m" denote the fracture and matrix domains, respectively.

The relative hydraulic conductivity is expressed by Mualem’s model [136] for fracture and matrix domains using Eq. 6.4 and Eq. 6.5.

$$K_{r,m,f} = \Theta_{m/f}^{I_{m/f}} \left[ \frac{\int_0^{\Theta_{m/f}} \frac{1}{h_{m/f}(x)} dx}{\int_0^1 \frac{1}{h_{m/f}(x)} dx} \right]^2$$  
(6.4)

$$\Theta_{m/f} = \frac{\theta_{m/f} - \theta_{r,m/f}}{\theta_{s,m/f} - \theta_{r,m/f}}$$  
(6.5)

where $0 \leq \Theta_{m/f} \leq 1.0$ is the effective saturation of the matrix or fracture domain, and $\theta_{s,m/f}$ and $\theta_{r,m/f}$ are volumetric saturated moisture content and volumetric residual moisture content in the matrix or fracture domain (subscripts "m/f" denotes matrix or fractures).

In this work the overall volumetric moisture content of the damaged material at saturation, $\theta_{s,d}$ was experimentally obtained for each degree of damage and $\theta_{r,m/f} = 0$ following [155]. $I_{m/f}$ is a parameter which has been described to account for tortuosity and pore connectivity [136]; a complete discussion of $I_m$ in cementitious material is presented in [13, 187, 160]. The values used in this work were taken from [187] and are reported in Section 6.6 along will all modeling.
parameters. The values and methods to determine the fracture tortuosity and pore connectivity parameter, \( I_f \), for cementitious materials, are not well studied, and therefore, the simplifying assumption of \( I_f = 1.0 \) was considered in this work, resulting in a first order linear model \[196, 35]\.

In order to integrate Eq. 6.4, the effective saturation must be expressed as a function of pressure head \( \Theta_{m/f} = \Theta_{m/f}(h_{m/f}) \). We use the van Genuchten model \[204, 203\] depicted in Eq. 6.6 for the matrix and fracture domain.

\[
\Theta_{m/f} = \frac{1}{1 + (\alpha_{m/f} h_{m/f})^{n_{m/f}}}^{m_{m/f}} \tag{6.6}
\]

where \( m_{m/f} = 1 - \frac{1}{n_{m/f}} \); \( \alpha_{m/f} [mm^{-1}] \) and \( n_{m/f} [dimensionless] \) are material parameters that are related to its pore size distribution. These parameters are obtained by fitting Eq. 6.6 to the experimentally obtained moisture-retention curves of the material. For cement-based materials, moisture-retention data (curves) are obtained by converting desorption isotherm of material to retention data using Kelvin-Laplace equation (Eq. 6.7) \[187, 64\] (i.e. converting \( \Theta(\text{Relative Humidity}) \) to \( \Theta(h) \)).

\[
h = \ln(RH)RT \tag{6.7}
\]

where \( R [JK^{-1}mol^{-1}] \) is the universal gas constant, \( T [K] \) is the temperature, and \( M [kg/mol] \) is the molecular mass, and \( g [9.81m/s^2] \) is the gravitational constant.

### 6.4.2 Determination of matrix domain parameters

Moisture transport parameters of matrix domain \( \alpha_m \) and \( n_m \) were determined from experimentally obtained desorption isotherms of undamaged material. It should be noted that we neglect hysteresis effect for simplicity. Methods to account for the hysteresis and its effects on the results are discussed in \[187\]. The saturated hydraulic conductivity of the matrix \( (K_{s,m}) \) was determined experimentally by performing measurements on undamaged material using Darcy’s Law and the equipment set developed in \[70\]. The volumetric moisture content at saturation \( (\theta_{s,m}) \) was determined experimentally by drying undamaged saturated material at 105°C and monitoring the mass loss. Mortar and concrete samples were saturated by placing them in lime-saturated water from the time of demolding for more than 12 months. The samples were never dried prior to mass-loss measurements to avoid air entrapment. This method follows \[110\]|168\], however, samples in this work were stored for a longer period under water. Undamaged material parameters are reported in the Results and Discussion section.
6.4.3 Determination of fracture domain parameters

It is not feasible to measure the unsaturated moisture transport parameters for the fracture domain including $\theta_{s,f}$, $K_{s,f}$, $\alpha_f$, and $n_f$. This is because, fractures cannot be saturated independent of a variably saturated matrix domain. Therefore, these parameters need to be obtained indirectly [146, 148, 117, 39, 100].

We calculate saturated moisture content of the fractures, $\theta_{s,f}$, using $\theta_{s,f} = \theta_{s,d} - \theta_{s,m}$, where $\theta_{s,d}$ is the saturated moisture content of a damaged material at a specific degree of damage and is measured experimentally. $\theta_{s,m}$ is the saturated moisture content of the undamaged material, discussed in section 6.4.2. Note that $\theta_{s,f}$ is equal to the volume fraction of the fracture phase, $v_f$.

The saturated hydraulic conductivity of a damaged material, $K_{s,d}$, can be calculated as weighted average of the saturated hydraulic conductivity of the fracture phase ($K_{s,f}$) and matrix phase ($K_{s,m}$), which is equal to the saturated hydraulic of undamaged material, per Eq. 6.8,

$$K_{s,d} = v_f K_{s,f} + (1 - v_f) K_{s,m}. \quad (6.8)$$

Equation 6.8 can be used to estimate $K_{s,f}$. The saturated hydraulic conductivity of the damaged material $K_{s,d}$, is measured experimentally by applying Darcys Law for each degree of damage. The same procedure was used for undamaged material to determine $K_{s,m}$. All other parameters in Eq. 6.8 are also experimentally measured as described above. The accuracy of the approximation of $K_{s,f}$ relies on the assumption that minimal expansion occurs during the damage process. In this study, $v_f$ is less than 6.2% in all degrees of damage, therefore, any increase in material volume is marginal and Eq. 6.8 remains a reasonable assumption. The weighted average model presented here for $K_{s,f}$ is a rational model for distributed cracking, where $K_{s,f}$ is generally 1-3 orders of magnitude larger than $K_{s,m}$. The obtained values of $K_{s,f}$, reported in the Results and Discussion section, are consistent with experimental values in [3].

To obtain moisture retention parameters of fracture domain ($\alpha_f$ and $n_f$), we subtract the experimentally measured moisture retention curve of the undamaged materials from that of the damaged materials. Then, Eq. 6.6 is fitted to the resulting retention curve of the fracture domain to determine $\alpha_f$ and $n_f$. The implicit assumption here is that the difference in the damaged and undamaged moisture retention curves is the sole effect of distributed fractures. The parameters for all the degrees of damage are reported in Section 6.6.
In this section, after providing a brief background on fracture-matrix moisture transfer, we propose a model for the moisture transfer coefficient, \( \beta_w \). The linear-transfer coefficient, \( \beta_w \), describes the boundary condition for the flux of incompressible moisture between the crack surface and undamaged material matrix. Traditionally, the fracture-matrix moisture transfer coefficient is estimated based on: (1) the structured block model [213], (2) the hydraulic conductivity at the matrix-fracture interface [68], and (3) the roughness of the fracture-matrix interface [39]. A comprehensive review of moisture transference in dual-permeable porous geologic materials is provided in [39]. However, due to the largely heterogeneous microstructure of damaged cementitious material, the structured matrix block model is not a good representation of damaged cementitious materials [49, 201]. In damaged cementitious materials, the damaged matrix blocks have vastly different sizes, shapes, fracture-interface roughness, and are not evenly structured as may be observed in some earth materials. Therefore, models proposed for \( \beta_w \) for soil and earth material using the uniformly structured matrix-block approach [185, 213, 69] does not well represent the heterogeneous nature of damaged cementitious materials.

Previously, some models accounting for hydraulic interaction of fractures and material matrix have been presented for cementitious material (discussed in [43]). However, these fracture-matrix transfer models are not dependent on capillary pressure gradient and generally assume a constant transfer rate. For this reason, the authors present a model for \( \beta_w \) in damaged cementitious material.

In the present work, rather than using the structured matrix block approach, the model is based on fracture sizes, which are rather well-studied in damaged cementitious materials and are more easily quantifiable [224]. The explicit assumptions in our proposed model for \( \beta_w \) are: (1) interfacial hydraulic potential is continuous at all degrees of saturation [80], that is, no transition region exists between the boundary of a fracture and the undamaged matrix that can increase or impede moisture transfer (such as, mineral deposits, carbonation, deposition of damage products, etc.), (2) \( \beta_w \) increases proportionally to the product of saturated hydraulic conductivity of the fracture domain and matrix domain, i.e, \( \beta_w \propto K_{s,f} K_{s,m} \), (3) \( \beta_w \) changes as a function of fracture width and (4) \( \beta_w \) decreases with increasing fluid viscosity.

To derive a mathematical model for \( \beta_w \), we consider tube model with circular cross-section for the fracture, schematically shown in Figure 6.2. Note that other fracture geometries, such as parallel plate model, may be equally considered (a comprehensive list is provided in [172]) and will result in the same model for \( \beta_w \). The transfer rate of moisture between the matrix and the cylindrical fracture is a function of the diameter, \( d_f [mm] \), to cross-sectional area, \( A_f [mm^2] \). The transfer rate increases as \( d_f \) decreases. This linear proportionality, \( \xi \), is written as \( \xi = \frac{d_f}{A_f} \).
Figure 6.2: Schematic of the moisture transfer model and capillary pressure conditions
Finally, inverse proportionality to kinematic viscosity from assumption (4) is included - meaning at lower viscosities the rate coefficient increases. The equation for $\beta_w$ used in this work is therefore Eq. 6.9.

$$\beta_w = \frac{\xi K_{s,f} K_{s,m}}{\nu}. \quad (6.9)$$

To implement Eq. 6.9, fracture diameters, $d_f$, are required ($\xi = \frac{d_f}{A_f}$). In this work, using CAD software, fracture diameters were measured from SEM images of concrete and mortar specimens with 11 levels of freeze-thaw damage ranging from 6% to 48% (further detail of freeze-thaw damage and damage quantification is provided in Section 6.5). For each damage level, fracture diameters were measured closest to the intersections of an evenly spaced grid of 25 nodes on 5 different SEM images. For concrete and mortar with freeze-thaw damage, $D$, average fracture diameters from the 25 measurements are shown in Figure 6.3. These values are consistent with [224], where mean fracture diameters ranging from approximately 1.5 to 3.5 $\mu$m in concrete with distributed drying-induced microcracking is reported.

The fitted exponential equation to the results shown in Fig. 6.3 is given by Eq. 6.10

$$d_f[\mu m] = 0.12 \cdot \exp(5.9D). \quad (6.10)$$
It should be noted that the coefficients in Eq. 6.10 do not have any physical significance and only the exponential form of the equation indicates that the average crack width increases exponentially with damage. By substituting the numerical value of $d_f$ from Eq. 6.10 in Eq. 6.9 and using $\nu$ of water at standard room temperature, the numerical values for $\beta_w$ can be calculated. In this paper, $\beta_w$ is expressed in [mm$^{-1}$hr$^{-1}$].

To illustrate the effect of $\beta_w$, the results of simulation of absorption behavior of a damaged material is shown in Fig. 6.4 where $\beta_w$ varies five orders of magnitudes. In these simulations, only $\beta_w$ changes. Fig. 6.4 shows that $\beta_w$ mainly influences the late-stage absorption with little to no effect on the initial sorption. This is expected since, in the late-stage absorption, the capillary pressure difference between fracture and matrix ($h_f - h_m$) approaches zero and the rate of moisture absorption is largely controlled by the magnitude of $\beta_w$. While in the present work the focus is on moisture transfer between fracture and matrix phases, in systems containing air or internal water reservoir (such as LWA and SAP) $\beta_w$ represents transfer from or to these phases. Values of $\beta_w$ proposed for geologic materials are generally in the lower range of the values shown in Fig. 6.4. Therefore, adopting values for $\beta_w$ that are proposed for geologic materials would underestimate the rate of fracture-matrix moisture transfer in cementitious materials.

![Figure 6.4: Effect of the moisture transfer rate coefficient on absorption for M48](image)

Figure 6.4: Effect of the moisture transfer rate coefficient on absorption for M48
6.4.5 Numerical simulation

For the numerical solution of both classical and dual-permeability models, a commercially available finite element package, HYDRUS 2D [215], was used. The material parameters for fracture and matrix domains are tabulated in the results section. The sorption test was modeled in 2D with rectangular dimensions of 25 mm x 100 mm for mortar and concrete specimens. Uniform initial moisture conditions, $\theta_i [mm^3/mm^3]$, were applied in all simulations and their values are tabulated in the results section. In general, $\theta_i$ is non-uniform and the initial spatial distribution of moisture is unknown; however the simplifying assumption of uniform initial moisture content was necessary for simulations. Since $\theta_i$ is generally low (0.01 - 0.03), the effect of spatially varying initial moisture content has only marginal effect. Zero-flux boundary conditions were applied to the top and sides of the specimen and a saturated boundary condition was applied to the bottom, which was in contact with water, simulating ASTM C1585 [11] absorption testing procedure. Finite element modeling was conducted using triangular elements with a maximum dimension of 1.0 mm and solved in terms of moisture content.

6.5 Materials and methods

6.5.1 Materials

Concrete

Concrete used in this work was made with ordinary Type I Portland cement and a water-to-cementitious (w/cm) ratio of 0.50. Class F fly ash was used to replace 24% of the cement by weight. Crushed limestone coarse aggregate with a maximum size of 19 mm and a natural river sand with a fineness modulus of 2.67 were used. The concrete was produced by a local ready-mix producer according to ASTM C94 [12]. Table 6.1 summarizes the mixture proportions of concrete.

The concrete mixture was cast in 100 mm x 200 mm cylinders and kept sealed for 24 hours. Cylinders were then cut into 25 mm thick disks with a wet-saw. After cutting, the specimens were cured in lime-saturated water at 25±1°C for over 12 months. Concrete specimens were then subjected to freeze-thaw loading to induce different degrees of damage. The degree of damage was quantified using the change in elastic stress wave travel time quantified using acoustic emission following [70]; further details are provided in Section 6.5.3.

Mortar

Mortar used in this work was cast with a water-to-cement (w/c) ratio of 0.42 using ordinary Type I Portland cement and a natural river sand with a fineness modulus of 2.65. No mineral
admixtures were used. Table 6.1 summarizes the mixture proportions of the mortar.

The mortar mixture was cast in 100 mm x 200 mm cylinders and kept sealed for 24 hours. Cylinders were then saw-cut into 25 mm thick disks. After cutting, the specimens were cured in lime-saturated water at 25±1°C for over 12 months. Mortar specimens were then subjected to different degrees of freeze-thaw damage. Damage was measured similar to concrete specimens.

Table 6.1: Mix proportions of mortar and concrete

<table>
<thead>
<tr>
<th>Proportions</th>
<th>Concrete</th>
<th>Mortar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement, Type I [kg/m³]</td>
<td>261</td>
<td>609</td>
</tr>
<tr>
<td>Fly Ash, Type F [kg/m³]</td>
<td>83</td>
<td>0</td>
</tr>
<tr>
<td>Water [kg/m³]</td>
<td>232</td>
<td>255</td>
</tr>
<tr>
<td>Coarse Aggregate [kg/m³]</td>
<td>1073</td>
<td>0</td>
</tr>
<tr>
<td>Fine Aggregate [kg/m³]</td>
<td>747</td>
<td>1466</td>
</tr>
<tr>
<td>Water Reducer [kg/m³]</td>
<td>1.70</td>
<td>3.00</td>
</tr>
<tr>
<td>w/cm</td>
<td>0.50</td>
<td>0.42</td>
</tr>
<tr>
<td>Cement Paste Volume Fraction</td>
<td>0.31</td>
<td>0.45</td>
</tr>
</tbody>
</table>
6.5.2 Freeze-thaw loading

Freeze-thaw loading of concrete and mortar was performed in an air-cooled chamber following procedures in [110]. To keep the specimens saturated during the freeze-thaw testing, they were wrapped in a water-saturated cloth and then sealed with a thin plastic sheet. To reach approximately similar degrees of damage in concrete and mortar, different temperature profiles and number of freeze-thaw cycles were used for each material.

In the case of concrete materials, the freeze-thaw cycle duration was 12 hours. The cycle consisted of a 2 hour cooling period from 20 to -23°C, 4 hour rest period at -23°C, 2 hour heating period from -23 to 20°C, and 4 hour rest period at 20°C. A maximum of 5 cycles was used for concrete. Concrete with degrees of damage of 21%, 29%, and 47% damage were achieved using 2, 3, and 5 cycles, respectively.

In the case of mortar, each cycle was 4 hours including a cooling period from 21°C to -35°C and a heating period back to 21°C. A maximum 25 cycles were used for mortar. Mortar with degrees of damage of 18%, 30%, and 48% were obtained using 10, 15, and 25 cycles, respectively.

6.5.3 Method of quantifying freeze-thaw damage

The degree of damage after a given number of freeze-thaw cycles was quantified using the change in the travel time of elastic stress wave which was measured using active acoustic emission similar to [70][110]. Active acoustic emission describes a method in which a series of pulse (four discrete pulses in this work) is sent by an acoustic emission sensor and is captured by another sensor (pitch-catch). Then, the order of sending and receiving the pulse is switched between the two sensors. The signal transmission time is measured for all the pulses and the average value is reported (average of eight measurements).

In the active acoustic emission measurements, sensors with a peak frequency of 375 kHz were used. Sensors were installed on opposite sides of the 25 mm thick disk specimens that were slightly trimmed tangent to the edge to produce a flat surface for proper installation of the sensors. Disk specimens were then placed on a layer of acoustic mat on a rigid, stainless steel frame. A stainless steel rod was used as a reference to monitor environmental noise during the testing. Damage was estimated based on the wave travel time in undamaged and damaged specimens and calculating the relative elastic modulus:

\[
D = 1 - \frac{E_t}{E_0} = 1 - \left( \frac{t_0}{t_t} \right)^2
\]  \hspace{1cm} (6.11)

where \(E_t\) is the dynamic elastic modulus after freeze-thaw damage, \(E_0\) is the initial dynamic elastic modulus (before freeze-thaw damage), \(t_t\) is the signal transmission time after freeze thaw,
and $t_0$ is the signal transmission time before freeze-thaw damage. In Eq. 6.11, the change in density of the damaged material is considered negligible.

### 6.5.4 Desorption isotherm

#### Concrete

The concrete specimens with different degrees of damage were conditioned at six relative humidities using four saturated salt solutions with relative humidity of 32.8%, 75.3%, 85.1%, and 93.6% and two environmental chambers with relative humidity of 50%, and 65%. A total of three replicate specimens for each degree of damage were used and all measurements were performed at $23\pm1^\circ$C.

A total of 108 samples were used. The average weight of the specimens was 52.5 g with a standard deviation (SD) of 5.2 g. The average thickness of the specimens was 5.62 mm (with a SD of 1.29 mm). After 6 months conditioning, specimens were weighed using an analytical balance with 0.10 mg resolution in one month intervals until equilibrium which was defined as variation of less than 1.0 mg/month.

#### Mortar

To measure desorption isotherm of mortar specimens with different degrees of damage, an automated vapor sorption analyzer was used. Small samples (0.5-1.5 mm thick and 50-100 mg weight) were used. The samples, with an average dimension of approximately 1.0 mm, well represent the bulk material as the maximum fracture width was less than 25 µm in all cases. The mass of the specimens were monitored while the relative humidity was sequentially dropped from 97.5% to 0% RH, with a 5% RH decrease between each successive step after reaching equilibrium. Equilibrium was defined as a mass change less than 0.001 mg within 15 minutes, similar to [187]. This criterion was previously studied and verified in [156, 8, 65].

### 6.5.5 Saturated hydraulic conductivity

The saturated hydraulic conductivity measurements were performed using an in-house developed equipment [70]. Measurements were performed on 25 mm thick disks. Before the measurements, the perimeter of the specimens were coated with a rapid-setting epoxy. The disks were never dried. A total of 3 replicates were used for concrete and a total of 4 replicates were used for mortar at each degree of damage. All the measurements were performed in a temperature controlled room at $23\pm1^\circ$C. Further details of saturated hydraulic conductivity can be found in [70].
6.5.6 Volumetric moisture content

After the conditioning period in lime-saturated water for over 12 months, mortar and concrete disk samples were dried at 105°C for 48 hours to calculate volumetric water content, $\theta_s$. Note that these samples that were used to measure $\theta_s$ were discarded after measurement and were not used in further any the experiments.

6.5.7 Water absorption test

In this work, water absorption was carried out following ASTM C1585 [11] where the specimens were placed in contact with water and the mass of the specimens were monitored over time. The measurements were carried out up to 90 days. The specimens were conditioned according to ASTM C1585, requiring drying of the specimen at 50°C. It is assumed that this drying did not induce further damage, since large temperature gradients are not present across the sample in this procedure. Prior to the experiments, the perimeter of the specimens was sealed using epoxy. To avoid contamination of circular cross-sectional surfaces with epoxy, the samples were covered with pieces of paper during the application of epoxy. The top circular cross-sectional surface, which was not in contact with water, was covered with a layer of plastic that was secured to the specimen with a rubber band as specified by ASTM C1585 and similar to the works by Castro (2011) [33].

6.6 Results and discussion

6.6.1 Experimentally obtained modeling parameters

The experimentally obtained desorption isotherms of mortar and concrete are depicted in Figure 6.5a and 6.5b, respectively; in Figure 6.5 "C” and "M” stand for Concrete and Mortar, respectively, and the number following them indicates the degree of damage. In both materials, the desorption isotherms show a higher moisture retention with increasing damage. This is expected as damage increases the overall porosity of the system [70]. Tables 6.2 and 6.3, respectively, report the dual-permeability and classical model hydraulic parameters for mortar and concrete with all degrees of damage.

---

1"C” and "M” stand for Concrete and Mortar, respectively, and the number following them indicates the degree of damage.
Figure 6.5: Desorption isotherms for different degrees of damage, (a) mortar, (b) concrete; "C" and "M" stand for Concrete and Mortar, respectively, and the number following them indicates the degree of damage.

Table 6.2: Dual-Permeability Model Hydraulic Parameters for Damaged Mortar and Concrete

<table>
<thead>
<tr>
<th>Parameters</th>
<th>M0</th>
<th>M18</th>
<th>M30</th>
<th>M48</th>
<th>C0</th>
<th>C21</th>
<th>C29</th>
<th>C47</th>
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</thead>
<tbody>
<tr>
<td>$K_{s,f} \left( \frac{mm}{hr} \right)$</td>
<td>-</td>
<td>3.5·10^{-2}</td>
<td>5.3·10^{-2}</td>
<td>5.6·10^{-2}</td>
<td>-</td>
<td>1.1·10^{-1}</td>
<td>1.2·10^{-1}</td>
<td>3.1·10^{-1}</td>
</tr>
<tr>
<td>$K_{s,m} \left( \frac{mm}{hr} \right)$</td>
<td>3.0·10^{-5}</td>
<td>3.0·10^{-5}</td>
<td>3.0·10^{-5}</td>
<td>3.0·10^{-5}</td>
<td>1.4·10^{-4}</td>
<td>1.4·10^{-4}</td>
<td>1.4·10^{-4}</td>
<td>1.4·10^{-4}</td>
</tr>
<tr>
<td>$\beta_w \left( \frac{mm}{hr} \right)$</td>
<td>-</td>
<td>2.0·10^{-6}</td>
<td>7.0·10^{-6}</td>
<td>2.0·10^{-6}</td>
<td>-</td>
<td>2.0·10^{-5}</td>
<td>3.0·10^{-5}</td>
<td>3.0·10^{-5}</td>
</tr>
<tr>
<td>$\alpha_m \left( \frac{1}{mm} \right)$</td>
<td>1.2·10^{-2}</td>
<td>1.2·10^{-2}</td>
<td>1.2·10^{-2}</td>
<td>1.2·10^{-2}</td>
<td>6.4·10^{-2}</td>
<td>6.4·10^{-2}</td>
<td>6.4·10^{-2}</td>
<td>6.4·10^{-2}</td>
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<tr>
<td>$\alpha_f \left( \frac{1}{mm^2} \right)$</td>
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<td>2.9·10^{-2}</td>
<td>1.5·10^{-2}</td>
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<tr>
<td>$n_f [-]$</td>
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<td>1.7</td>
<td>1.6</td>
<td>1.9</td>
<td>-</td>
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<td>$I_m [-]$</td>
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<td>-4.0</td>
<td>-4.0</td>
<td>-3.0</td>
<td>-3.0</td>
<td>-3.0</td>
<td>-3.0</td>
</tr>
<tr>
<td>$I_f [-]$</td>
<td>-</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>-</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$\theta_i \left( \frac{mm^3}{mm^3} \right)$</td>
<td>0.030</td>
<td>0.010</td>
<td>0.020</td>
<td>0.010</td>
<td>0.030</td>
<td>0.040</td>
<td>0.030</td>
<td>0.030</td>
</tr>
<tr>
<td>$\theta_{s,m} \left( \frac{mm^3}{mm^3} \right)$</td>
<td>0.140</td>
<td>0.140</td>
<td>0.140</td>
<td>0.140</td>
<td>0.150</td>
<td>0.150</td>
<td>0.150</td>
<td>0.150</td>
</tr>
<tr>
<td>$v_f \left( \frac{mm}{mm^3} \right)$</td>
<td>-</td>
<td>0.016</td>
<td>0.036</td>
<td>0.060</td>
<td>-</td>
<td>0.012</td>
<td>0.020</td>
<td>0.042</td>
</tr>
</tbody>
</table>
### Table 6.3: Classical Model Hydraulic Parameters for Damaged Mortar and Concrete

<table>
<thead>
<tr>
<th>Parameters</th>
<th>M0</th>
<th>M18</th>
<th>M30</th>
<th>M48</th>
<th>C0</th>
<th>C21</th>
<th>C29</th>
<th>C47</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{s,d}[mm/hr]$</td>
<td>-</td>
<td>5.9·10^{-4}</td>
<td>1.9·10^{-3}</td>
<td>3.4·10^{-3}</td>
<td>-</td>
<td>1.4·10^{-3}</td>
<td>2.6·10^{-3}</td>
<td>1.3·10^{-2}</td>
</tr>
<tr>
<td>$\alpha[1/mm]$</td>
<td>-</td>
<td>1.8·10^{-2}</td>
<td>3.3·10^{-2}</td>
<td>1.7·10^{-2}</td>
<td>-</td>
<td>4.6·10^{-2}</td>
<td>4.6·10^{-2}</td>
<td>4.3·10^{-2}</td>
</tr>
<tr>
<td>$n[-]$</td>
<td>-</td>
<td>1.8</td>
<td>1.5</td>
<td>1.8</td>
<td>-</td>
<td>2.5</td>
<td>2.5</td>
<td>2.3</td>
</tr>
<tr>
<td>$I[-]$</td>
<td>-</td>
<td>-8.0</td>
<td>-8.0</td>
<td>-8.0</td>
<td>-7.0</td>
<td>-6.0</td>
<td>-5.0</td>
<td></td>
</tr>
<tr>
<td>$\theta_i[mm^3/mm^3]$</td>
<td>-</td>
<td>0.010</td>
<td>0.020</td>
<td>0.010</td>
<td>-</td>
<td>0.040</td>
<td>0.030</td>
<td>0.030</td>
</tr>
<tr>
<td>$\theta_{s,d}[mm^3/mm^3]$</td>
<td>-</td>
<td>0.156</td>
<td>0.176</td>
<td>0.200</td>
<td>-</td>
<td>0.162</td>
<td>0.170</td>
<td>0.192</td>
</tr>
</tbody>
</table>

### 6.6.2 Simulation of absorption in mortar and concrete

The experimental results of water absorption in mortar and concrete, with comparative levels of damage, and the results of numerical simulations using both classical and dual-permeability models are presented in Figure 6.6. The experimental results, at each degree of damage, in Figure 6.6, are an average of measurements on three replicate specimens. All results are reported as volume of water [$mm^3$] absorbed per absorbing area [$mm^2$]. All results are plotted against the square root of time [$day^{1/2}$], with the results of concrete and mortar shown in the left and right columns, respectively.

In general, the simulation results from the classical and dual-permeability models compare well with experimental results. In all cases, the dual-permeability model underestimates the experimental results at early stages of water absorption, while the classical model more closely estimates the experimental results during the early stages. This is mainly because the capillary suction is the main mechanism of transport at early stages of water absorption.

In contrast to the early stages of water absorption, at the later stages, the dual-permeability model more closely estimates the experimental results as compared to the classical isothermal model. The improved accuracy of the dual-permeability in modeling the late stages is due to explicit modeling of moisture transfer between matrix and fracture phases. This transfer is especially slow at high degrees of saturation due to the low capillary pressure gradient between the matrix and fracture domains. Therefore, unlike the results from the classical model where saturation of materials occurs very rapidly (e.g., M48 and C47 materials saturate after approximately 1 day in classical simulations), rapid saturation does not occur in dual-permeability simulations.

The better performance of the dual permeability model, as compared to the classical model, in modeling the late stages of moisture absorption is shown in Figure 6.7, where the 90-day cumulative moisture absorption [$mm^3/mm^2$] estimated with the dual-permeability and the classical models are compared with experimental results. For all degrees of damage, it is clear
Figure 6.6: Comparison of the experimental absorption measurements with dual-permeability and classical isothermal simulations for damaged concrete (left column) and damaged mortar (right column); (a) C21, (b) C29, (c) C47, (d) M18, (e) M30, and (f) M48
that the dual-permeability model better estimates the experimental results. Especially, in the case of M48 and C47 which have the highest damage levels and where the volume fraction of fracture phase ($v_f$) are the highest, the late-stage results of dual-permeability model compare most favorably with experimental results.

![Figure 6.7: Cumulative ingress in mortar and concrete; (a) Mortar, (b) Concrete](image)

We would like to discuss, for clarity and completeness, a few points in using the dual-permeability model and the proposed approaches in this paper for indirectly obtaining the material parameters needed for using dual-permeability model.

The dual-permeability simulations can be numerically unstable at very low values of $I_m$ and the simulations very often do not converge at low values of $I_m$. In such instances, it becomes necessary to use a higher value for $I_m$. In the present work, $I_m$ was raised from -9.0 and -7.0 to -4.0 and -3.0 in mortar and concrete, respectively. These values are higher than those proposed in [187]. Increasing the magnitude of $I_m$ results in lower hydraulic conductivity at low levels of saturation, and therefore, a reduced rate of initial absorption as was observed in Figure 6.6.

The dual permeability model, used in this work, employed a linear moisture transfer model, $\Gamma = \beta_w (h_f - h_m)$, which may underestimate initial moisture absorption. Köhne et al. (2004) [100], Zimmerman et al. (1993) [234], and Gerke and van Genuchten (1993) [68] noted that moisture transfer in early-stage moisture ingress in dual-permeability models may be highly transient and transfer is commonly underestimated with the linear transfer models. One proposed solution from [68] was nonlinear moisture transfer, $\Gamma = \beta_w (h_f - h_m)^z$, where $z > 1.0$ increased early-stage moisture transfer rates. Non-linear models are not included in the implementation of [215] that was used in the present work, and therefore, were not considered herein. It is unclear whether such models will improve simulations at all stages of ingress and further
investigations in using nonlinear models are much needed. One potentially useful approach may be the use of inverse analysis to obtain nonlinear parameters for a given model, or equally for a set of models.

Finally, indirectly obtaining fracture phase parameters including unsaturated moisture transport parameters ($\theta_{s,f}$, $K_{s,f}$, $\alpha_f$, and $n_f$) and its saturated hydraulic conductivity ($K_{s,f}$) introduces uncertainties and errors into modeling. These estimations are dependent on the assumptions used. For example, in this work, we used the so-called “rule of mixtures” to estimate $K_{s,f}$ from the saturated hydraulic conductivity of the undamaged and damaged materials. This is essentially a first-order linear model which of course has limitations. Much needed are methods for direct or indirect estimation of fracture phase parameters with lower uncertainties.

6.7 Summary and conclusions

In this paper, we investigated whether dual-permeability modeling approach can be used to more accurately model unsaturated moisture flow in damaged mortar and concrete materials. We compared the results of dual-permeability simulations with those of classical isothermal model against experimentally measured data. In simulations of moisture transport with classical isothermal model, a homogenized material model that averages properties of matrix and fracture phase was used. In the dual-permeability model, the matrix and fracture phases were explicitly modeled and a linear moisture transfer between fracture and matrix phases was considered. We also proposed a model for the moisture transfer coefficient. Damaged and undamaged material properties were found experimentally and new methods of determining moisture transport parameters for the fracture phase in the dual-permeability model were proposed.

Simulation results indicate that the dual-permeability model well simulates moisture transport in late stages of moisture ingress, whereas, classical isothermal model provides a better estimate of the initial stages of moisture ingress. We also discussed difficulties that might arise in using the dual-permeability model.
Chapter 7

Conclusions

The broad aims of this thesis were to i) develop qualitative and quantitative electrically-based tomography to image 3D unsaturated moisture flow in cement-based materials and ii) develop material models and numerical techniques to simulate unsaturated moisture flow in damaged cement-based materials. Both aims were accomplished.

Chapter 2 was the first effort in visualizing 3D moisture flow in cement-based materials using an electrical-based method. The use of ERT to spatially and temporally monitor 3D flow was investigated using a qualitative method. Using fluids of differing viscosity and surface tension, corroborated with moisture flow simulations and X-ray computed tomography, ERT was shown to well-capture early-stages of flow. ERT reconstructions clearly distinguish between flow rates of the differing fluids. At advanced stages of flow (>22 hours of ingress), the qualitative scheme’s reconstructions had significant artifacts. Results indicated that ERT better captured low degrees of saturation than X-ray computed tomography (CT) due to the large sample size and attenuation of cement-based materials.

Chapter 3 developed a quantitative ERT scheme to capture 3D moisture flow in cement-based material. In the scheme, an iterative technique for solving the full ERT inverse problem was used. Results indicated that the quantitative scheme accurately depicted flow at all stages of moisture ingress when corroborated with moisture flow simulations. As in Chapter 2, ERT was shown to better reconstruct low degrees of moisture saturation than X-ray CT.

In Chapter 4, the use of ERT to visualize 3D moisture flow in cement-based material with physically-simulated and loading-induced discrete cracks was studied. This was done using an imaging method similar to that used in Chapter 3, but employing model-error term. Firstly, ingress of water into physically-simulated cracks of various geometry was monitored using ERT and corroborated with moisture flow simulations. The results of the corroboration showed that ERT well-captured progressive flow from the physically-simulated cracks. Following, ingress into loading-induced discrete cracks was investigated. ERT reconstruction were shown to well
visualize flow into cracks and capture progressive flow into the material surrounding the cracks.

The focus of Chapter 5 was moisture transport material modeling and simulation of unsaturated moisture flow in cement-based materials with distributed damage. The chapter first developed a hybrid van Genuchten-Mualem model to describe the water retention and unsaturated hydraulic conductivity considering hysteresis. In developing the material model, experimental measurements were used in determining all transport properties. Following, the finite element method was used for simulating unsaturated flow. Simulation results of water ingress were then corroborated with experiments. The results indicated that simulations well-capture early-stage flow, but deviate from experiment during secondary absorption.

Chapter 6 investigated whether the dual-permeability model may be used for simulating unsaturated moisture flow in cement-based materials with distributed damage. In this effort, hydraulic material models were developed for distributed fractures, the undamaged material matrix, and transient flow between the phases. The hydraulic models were then used in finite element simulations, which were corroborated with simulations from Chapter 5 and sorption experiments. Results indicated that the dual-permeability model may be used for simulating unsaturated flow. Moreover, long-term absorption was more accurately modeled using dual-permeability than the model developed in Chapter 5.
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