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1 **Modeling Water Absorption in Concrete and Mortar with Distributed Damage**

2
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4 **Abstract**

5
6 The deterioration rate of concrete structures is directly influenced by the rate of moisture
7 ingress. Modeling moisture ingress in concrete is therefore essential for quantitative
8 estimation of the service life of concrete structures. While models for saturated moisture
9 transport are commonly used, concrete, during its service life, is rarely saturated and some
10 degree of damage is often present. In this work, we investigate whether classical isothermal
11 unsaturated moisture transport can be used to simulate moisture ingress in damaged mortar
12 and concrete and we compare the results of numerical simulations with experimental
13 measurements of water sorption. The effect of hysteresis of moisture retention is also
14 considered in the numerical simulations. The results indicate that the unsaturated moisture
15 transport models well simulate early stages of moisture ingress at all damage levels, where
16 capillary suction is the prominent mechanism. At later stages of moisture transport, where air
17 diffusion and dissolution have a more significant contribution, simulations that consider
18 moisture hysteresis compare most favorably with experimental results.

19
20 **Author Keywords:** Cracking; Distributed Damage; Durability; Finite Element Method;
21 Mass Transport; Numerical Modeling; Unsaturated Mass Transport

22
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28 **1. Introduction**

29 The rate of freeze-thaw deterioration, chemical attack, corrosion of reinforcement, and
30 many other deleterious processes in concrete structures are strongly dependent on the rate of
31 moisture ingress. The rate of moisture ingress is heavily influenced by the degree of
32 saturation and the presence of damage. Concrete, during its service life, is rarely saturated
33 and some degree of damage is often present (e.g., due to freeze-thaw). Distributed damage in
34 concrete significantly increases the rate and the amount of moisture ingress ([Ghasemzadeh et](#)
35 [al. \(2016\)](#), Yang et al. (2004), Hearn (1999), Aldea et al. (1999)). While unsaturated moisture
36 transport in concrete material has been studied (e.g. Lockington et al. (1999), Martys et al.
37 (1997), Hall (1989)), limited research exists on unsaturated moisture transport in *damaged*
38 concrete ([M’Jahad et al. \(2014\)](#), [Wang and Ueda \(2014\)](#), [Mu et al. \(2013\)](#), [Zhou et al.](#)
39 [\(2012\(a\)\)](#), [Zhou et al. \(2012\(b\)\)](#), [Gérard and Marchand \(2000\)](#)). Specifically, modeling
40 studies on unsaturated moisture transport in damaged cementitious material are very scarce
41 ([Van Bellegem et al. \(2016\)](#), [Grassl \(2009\)](#), [Carmeliet et al. \(2004\)](#), [Daïan and Saliba](#)
42 [\(1993\)](#)). In this paper, we investigate the accuracy of the classical model (including
43 hysteresis) for simulating unsaturated water absorption in damaged mortar and concrete.

44 The majority of the previous studies on moisture transport in damaged cementitious
45 material were experimental in nature. These studies have shown that, for example, chloride
46 migration (as tested by Rapid Chloride Permeability Testing) increases in concrete after
47 subjecting concrete to compressive loading above 75% of its compressive strength (Samaha
48 and Hover, (1992)); Wang et al. (1997) found that water permeability generally increases
49 with damage; Aldea et al. (1999) found that discrete cracks have a significant effect on water
50 permeability; Rodriguez and Hooten (2003) found that chloride penetration increases in
51 damaged samples, irrespective of the presence of mineral admixtures; Picandet et al. (2009)
52 found that the permeability of discrete cracks increases proportional to the cube of the crack

53 opening displacement in specimens. They also showed that the use of fiber reinforcement
54 increases the crack tortuosity. In a recent study, the effects of distributed damage on mass
55 transport was shown to be dependent on the mechanisms of transport considered
56 (Ghasemzadeh and Pour-Ghaz (2014)).

57 The previous experimental studies have offered significant insights as to the effect of
58 damage on the mass transport properties of damaged cement-based material. While a
59 significant amount of experimental data for damaged cement-based materials are available in
60 the literature, the numerical simulation of unsaturated moisture flow in damaged cement-
61 based material is not well studied. In contrast, ~~for undamaged material,~~ numerous studies
62 have simulated moisture flow in undamaged materials (e.g., Huang et al. (2015)), Schneider
63 et al. (2012), Pour-Ghaz et al. (2009), Nguyen et al. (2008), and Bazant and Najjar (1972)).
64 Numerical simulations are of significant interest since many service-life prediction models
65 need to account for the effects of damage – characteristics which significantly affect moisture
66 flow in concrete structures (Scherer (2015)).

67 Recent examples studying moisture flow simulations in damaged cementitious material
68 include the followings. Grassl (2009) developed a lattice model, modeling 2D fractured
69 materials, to simulate moisture flow in concrete with distributed cracks. Pour-Ghaz et al.
70 (2009a, b) compared simulations of unsaturated moisture flow from saw-cuts, an idealized
71 crack, to X-ray radiography images. Van Belleghem et al. (2016) compared flow regimes
72 from numerical simulations of unsaturated moisture flow in discrete cracks with X-ray
73 images, showing good comparison between the numerical model and X-ray images. These
74 numerical investigations demonstrated the feasibility of numerical simulations of unsaturated
75 moisture flow in cement-based materials. However, neither the effects of varying degrees of
76 damage in the form of distributed cracks nor the effect of moisture retention hysteresis have
77 been studied.

78 The classical model describing unsaturated mass transport in porous media is Richards’
79 equation (Richards (1931)), modeling capillary suction. Richards’ equation has been
80 identified as a valid model for mass transport in building materials (Wilson et al. (1999)).
81 Analytical solutions to Richards’ equation have been developed for simple geometries (Cao
82 et al. (2014), Parlange et al. (1999), Parlange et al. (1997), Warrick et al. (1991)). Analytical
83 solutions are generally feasible in simple geometries subjected to simple boundary
84 conditions. Practical applications, however, often requires numerical solution to Richards’
85 equation using, for example, the Finite Element Method. The Finite Element Method
86 solutions of Richards’ equation have been used previously to analyze unsaturated moisture
87 transport in concrete (e.g. Van Bellegham et al. (2016) and Pour-Ghaz et al. (2009a,b)).
88 However, these studies investigated cementitious material with discrete cracks. Therefore the
89 feasibility of using classical isothermal unsaturated moisture transport to model moisture
90 ingress and moisture hysteresis in mortar and concrete with distributed damage remains an
91 open question.

92

93 **2 Numerical Methods**

94 **2.1 General**

95 In this paper, moisture absorption is modeled using the Richards’ Equation (Eq. 1)
96 (Richards (1931)) for unsaturated moisture flow. Equation 1 is the classical governing
97 differential equation for isothermal unsaturated flow

98

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i} \left[K(h) \left(\frac{\partial h}{\partial x_j} + \delta_{ij} \right) \right] \quad \text{Eq.1}$$

99

100 | where $K = K(h)$ (mm/hour) is the unsaturated hydraulic conductivity, θ (mm^3/mm^3) is the
 101 | volumetric moisture content, h (mm) is the [capillary suction](#), x_i (mm) is the spatial
 102 | coordinate ($i, j = 1, 2, 3$ for three dimensional space) and δ_{ij} is the Kronecker Delta function
 103 | which accounts for the gravitational effect. [Eq. 1 is generally solved using a numerical](#)
 104 | [methods such as finite element method. In this work we have used a commercially available](#)
 105 | [software \(HYDRUS 3D\) for this purpose and the details of modeling methods are discussed](#)
 106 | [in Section 2.4.](#)
 107 |

108 | 2.2 Material Model

109 | The unsaturated hydraulic conductivity (K) in Eq. 1 is a function of [capillary suction](#) (i.e.,
 110 | $K = K(h)$). Experimental measurements of unsaturated hydraulic conductivity are generally
 111 | difficult and time consuming. These measurements are especially challenging for cement-
 112 | based materials due to the fine pore size distribution resulting in high [capillary suction](#) at low
 113 | water contents (Pour-Ghaz et al. (2009a,b)). Alternatively, the unsaturated hydraulic
 114 | conductivity can be expressed as a product of the saturated hydraulic conductivity, K_s , and
 115 | the relative hydraulic conductivity, $0 < K_r < 1.0$ (i.e., $K = K_s K_r$). Such a model,
 116 | commonly used in soil physics, has been shown to well-represent the unsaturated hydraulic
 117 | conductivity in cement-based materials (Schneider et al. (2012), Poyet et al. (2011), Savage
 118 | and Janssen (1997)). The value of K_s can be experimentally measured using Darcy's law.
 119 | The relative hydraulic conductivity is related to water content and [capillary suction](#) by
 120 | Mualem's model (Mualem (1976)) (Eq. 2)
 121 |

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

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$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad \text{Eq.3}$$

122
123 where $0 \leq \Theta \leq 1.0$ is the effective material saturation, and θ_s and θ_r are the saturated
124 moisture content and the residual moisture content, respectively. In this work, θ_s is
125 experimentally obtained for each degree of damage and $\theta_r = 0$ (Pour-Ghaz et al. (2009a,b)).
126 Further discussion of determining θ_s is provided in the Materials and Methods section. I is
127 an empirical parameter which has been described as accounting for tortuosity and
128 connectivity of pores (Mualem (1976)). Mualem proposed $I = \frac{1}{2}$ as an optimal value for 45
129 undisturbed soils; however, he noted that values for I can take positive or negative values.
130 Values for soil have been shown to range from -8.83 to 100 (Schaap and Leij (2000), Yates
131 (1992), Schuh and Cline (1990)). Kosugi argued that I has no physical significance and
132 should be interpreted as a fitting parameter (Kosugi (1999)). Values of I for cementitious
133 materials and especially for damaged cementitious materials are not readily available.
134 Schneider et al. (2012) reported values of -3.0 and 35.2 for mortar and concrete, respectively.
135 Poyet et al. (2011) concluded that the values of I can take positive or negative values, but are
136 generally negative.

137 It should be noted that the choice of $\theta_r = 0$ is mainly for convenience since it does not
138 introduce a significant modeling error and does not require elaborate measurements. In
139 theory, the value of θ_r should correspond to the water content of the material at equilibrium
140 with 11% relative humidity. This condition results in the formation of a monolayer of
141 physically adsorbed moisture on calcium silicate hydrate (Alizadeh et al. 2007, Feldman and
142 Beaudoin (1983), Feldman and Beaudoin (1976), Feldman and Sereda (1970)) which can be
143 only achieved under extreme drying conditions. In this work, we choose $\theta_r = 0$ following

144 | [\(Pour-Ghaz et al. 2009\(a\), 2009\(b\)\)](#) to also avoid inconsistency in modeling between mortar
145 | [and concrete since the actual value of \$\theta_r\$ for concrete is unknown for our materials.](#)

146 | In this study, values of I are estimated by model training using maximum likelihood
147 | approach (Lay 2011). For such an approach the data need to be split into two sets: training
148 | and validation set. In this study only limited supply of experimental data is available. [In such](#)
149 | [situations, using cross-validation methods may provide more accurate solutions of \$I\$.](#)
150 | [However, cross-validation methods can be very computationally expensive due to the](#)
151 | [computational cost of moisture transport simulations.](#) We therefore use the maximum
152 | likelihood least squares fitting approach by splitting the experimental data into training and
153 | validation set using random number generators. Training set consisted of 33% of the data and
154 | validation set consisted of 67% of the entire data. Note that the training set was not used in
155 | comparison of the simulations and experiments results in the Results and Discussion section
156 | of this paper (only validation set was used). More information on the maximum likelihood
157 | least squares fitting approach can be found in (Lay (2011)).

158 | To integrate Eq. 2, the effective saturation should be expressed as a function [of capillary](#)
159 | [suction](#) (i.e., $\Theta = \Theta(h)$). Different models for $\Theta = \Theta(h)$ have been developed (Kosugi
160 | (1996), Brooks and Corey (1964)). The model proposed by van Genuchten (1980, 1985) is
161 | used in this study and is shown in Eq. 4

162

$$\Theta = \frac{1}{[1+(\alpha h)^n]^m}, m = 1 - \frac{1}{n} \quad \text{Eq.4}$$

163

164 | where α and n are fitting parameters (α , inversely proportional to the mean pore diameter
165 | (mm^{-1}) and n (non-dimensional) is the curve shape parameter). These fitting parameters are
166 | obtained by fitting Eq. 4 to experimentally obtained water retention curves using the least

167 squares method (Lay 2011). In the case of cement-based materials, instead of water retention,
168 $\Theta = \Theta(h)$, it is more common to measure the sorption isotherm of material (i.e., $\Theta =$
169 $\Theta(RH)$, $RH =$ relative humidity). The sorption isotherm can then be converted to retention
170 curve using Kelvin-Laplace Equation (Eq. 5) (Pour-Ghaz et al. (2009a), Leech et al. (2006),
171 [Bentz et al. \(1998\)](#)):
172

$$h = \frac{\ln(RH)RT}{V_m} \quad \text{Eq.5}$$

173
174 [where \$R\$ \(\$\text{J.K}^{-1} \text{mol}^{-1}\$ \) is universal gas constant, \$T\$ \(K\) is the temperature, and \$V_m\$ \(\$\text{m}^3/\text{mole}\$ \) is](#)
175 [the molecular weight of water.](#)
176

177 **2.3 Material Model with Moisture Retention Hysteresis**

178 The procedure for determining moisture retention curves described above is valid for both
179 drying and rewetting of the material. However, moisture retention curves obtained using an
180 initially-saturated specimen do not consider the effects of hysteresis. While the assumption
181 that the parameter n remains unchanged during hysteresis has been shown to be an acceptable
182 approximation (Nielsen and Luckner (1992), Kool and Parker (1987)), the re-wetting
183 hydraulic parameters α^w and θ_s^w should be separately determined for the hysteresis model.

184 Since obtaining adsorption isotherms generally requires significant experimental time due
185 to diffusion and dissolution of trapped air, which may be impractical in many cases, we use
186 an analytical expression for α^w and experimental data to determine θ_s^w . In addition, we
187 approximate that the saturated hydraulic conductivity, K_s , and tortuosity-pore connectivity
188 parameter, I , remain the same in both drying and re-wetting. Such approximations regarding
189 the parameters K_s and I may result in overestimation of initial sorptivity, as the magnitude of

190 saturated hydraulic conductivity often decreases after drying (Saeidpour and Wadsö (2016),
191 Baroghel- Bouny (2007), Mainguy et al. (2001)). Unfortunately, history-dependent data for
192 K_s and I in damaged cementitious material are nonexistent.

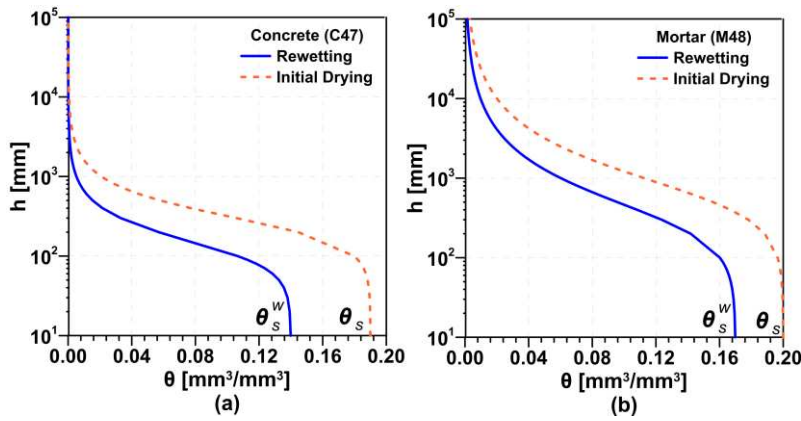
193 The re-wetting parameter α^w is physically related to the mean pore diameter after the first
194 drying cycle. In porous materials, α^w is generally larger than in the first drying case (i.e.
195 $\alpha^w > \alpha$), which is largely due to air-entry into the pore system. $\alpha^w = 2\alpha$ is commonly
196 accepted as a first approximation (Kool and Parker (1997)) and is used herein.

197 The saturated moisture content of a re-wetting material is less than that of the initial
198 saturation (i.e. $\theta_s > \theta_s^w$) due to the presence of air in large pores. Here we determine
199 θ_s^w using experimental absorption data (from the sorption test, discussed in Section 3.6). The
200 sorption measurements beyond 90 days show negligible mass gain of the samples and, as
201 such, it is assumed here that θ_s^w is equal to the saturated moisture content after 90 days of
202 rewetting. While this rough approximation may lead to slight underestimation of the
203 saturated moisture content of the rewetting material, it was found to be suitable for the
204 hysteresis model presented. Ingress is defined as, $i = \frac{V_w}{A}$, where $V_w(\text{mm}^3)$ and $A(\text{mm}^2)$ are the
205 volume of absorbed water and cross-sectional area of the absorbing specimen, respectively.
206 If assumed to be in a completely saturated state, we can approximate $i = \frac{V_w}{A} = \frac{\theta_s^w V_s}{A}$, where V_s
207 is the volume of the specimen. By rearranging, we obtain the expression for the re-wetting
208 volumetric saturated moisture content: $\theta_s^w = \frac{iA}{V_s}$.

209 The use of hydraulic parameters θ_s^w and α^w have significant implications on the moisture
210 retention curves of the re-wetting material. To illustrate this, Figure 1 shows drying and
211 rewetting moisture retention curves for concrete and mortar with the highest degrees of
212 damage. [We note that the initial drying curves shown in Figure 1 were determined by using](#)
213 [Eq. 5 to convert RH to h from the desorption isotherms. Then the complete curve was plotted](#)

214 | [by determining the fitting parameters in Eq. 4 using the experimental data. The rewetting](#)

215 | [curves were then determined for the same materials using \$\alpha^w = 2\alpha\$ and \$\theta_s^w = \frac{iA}{V_s}\$.](#)



216

217 | Figure 1: Drying and rewetting moisture retention curves; (a) concrete (C47) with a high
218 | degree of damage (47%) and (b) mortar (M48) with high degree of damage (48%).

219

220

221 | 2.4 Numerical Simulation and Experimental Corroboration

222 | In this work, a commercially available Finite Element Software, HYDRUS 3D, was used
223 | (Sejna et al. (2014)). The sorption test was simulated by modeling water sorption in a 100
224 | mm x 25 mm cylinder. Zero-flux boundary conditions were applied to all surfaces except the
225 | bottom surface where the sample was in contact with water. The boundary condition at the
226 | bottom surface was saturated boundary condition. Uniform initial moisture content, θ_i , were
227 | considered in this study; values for θ_i were experimentally obtained and are tabulated in the
228 | results section. It should be noted that the specimens used for sorption measurement were
229 | conditioned according to ASTM C1585, which does not guarantee a uniform initial moisture
230 | distribution. Achieving a uniform initial moisture distribution requires long-term
231 | conditioning, on the order of a few years (Castro (2011(a))). Therefore, in this work the
232 | simplifying assumption of uniform initial moisture condition was considered. The discussion
233 | of the effect of conditioning can be found in (Castro (2011(a))).

234 Finite element modeling consisted of tetrahedron elements with a maximum dimension of
235 1.0 mm. The finite element model was solved in terms of moisture content. [The material](#)
236 [parameters determined using the methods discussed in Section 2.2 and 2.3 \(reported in Tables](#)
237 [2 and 3, Section 4.2\) were input directly into the HYDRUS 3D.](#)

238

239 **3 Materials and Methods**

240 **3.1 Materials**

241 Both mortar and concrete were used. Table 1 reports the mixture proportions for concrete
242 and mortar. [It should be noted that the mixture proportions reported in Table 1 are for](#)
243 [saturated surface dry \(SSD\) fine and coarse aggregates.](#) No air entraining agent was used.
244 Entrapped air is taken in this work as a part of the open porosity. The open porosity of the
245 hardened material can be taken as the volumetric moisture content at saturation as discussed
246 in Hall and Hoff (2011). In this work, the volumetric moisture content at saturation was
247 experimentally measured. For both materials, cylindrical samples with dimensions 200 mm
248 x 100 mm ([100 mm diameter](#)) were cast. All specimens were cut into disks (25 mm x 100
249 mm) after 24 hours of sealed curing and then were stored for 12 months in lime saturated
250 water. This was done to ensure uniform saturation, minimize leaching, and to uniformly
251 mature the specimens. More detailed discussion of the benefits of lime-saturated curing may
252 be found in (Siddiqui et al. (2013)).

253

Table 1: Mix proportions of concrete and mortar

Proportions	Concrete	Mortar
Cement ^a (kg/m ³)	261	609
Fly Ash, Type F (kg/m ³)	83 ^b	---
Water (kg/m ³)	132.5	256
Coarse Aggregate ^c (kg/m ³)	1073	0
Fine Aggregate ^d (kg/m ³)	747	1466
Water Reducer (kg/m ³)	0.50	0.50
w/cm	0.50	0.42

^aOrdinary Type I portland cement

^b24% replacement by mass of cement

^cCrushed limestone (MSA = 19 mm)

^dNatural river sand, (FM = 2.67)

[Mixture proportions are for saturated surface dry \(SSD\) fine and coarse aggregates](#)

254

255

256 3.2 Freeze-Thaw Loading

257 Specimens were subjected to freeze-thaw loading in an air-cooled chamber to induce
 258 different degrees of damage following the procedure in Li et al. (2011). To keep the
 259 specimens saturated during testing, they were wrapped in water-saturated cloth and sealed in
 260 a thin plastic sheet. To obtain a similar degree of damage in mortar and concrete, different
 261 temperature profiles and number of cycles were used in each material.

262 In concrete, the freeze-thaw cycle lasted 12 hours. Each cycle consisted of a 2-hour cooling
 263 period from 20 to -23°C, a 4-hour rest period at -23°C, a 2-hour heating period from -23 to
 264 20°C, and a 4 hour rest period at 20°C. A maximum of 5 cycles were used in concrete.

265 In freeze-thaw loading of mortar, each cycle was 4 hours, including a cooling period from 21
 266 to -35°C and a heating period to 21°C. A maximum of 25 cycles was used in mortar.

267 Concrete specimens with five different degrees of damage (10, 21, 29, 36, and 47%) and
 268 mortar specimens with three different degrees of damage (18, 30, and 48%) were prepared.

269 The method of quantifying damages is provided in the next section.

270

271 3.3 Quantifying Damage due to Freeze-Thaw

272 The degree of damage after a given number of freeze-thaw cycles was quantified using the
273 change in dynamic elastic modulus using active acoustic emission similar to ([Rashetnia et al.](#)
274 [\(2016\)](#), Ghasemzadeh and Pour-Ghaz (2014), Li et al. (2011)). Active acoustic emission
275 describes a method in which a series of acoustic pulse (four discrete pulses in this work) is
276 sent by an acoustic emission sensor and is captured by another sensor (pitch-catch). Then, the
277 order of sending and receiving the pulse is switched between the two sensors. The signal
278 transmission time is measured for all the pulses and the average value is reported (average of
279 eight measurements). Acoustic emission sensors with a peak frequency of 375 kHz were
280 used. Sensors were installed on opposite sides of 25 mm thick disk specimens, the perimeter
281 of which were slightly trimmed tangent to the edge to properly install the sensors. Disk
282 specimens were then placed on a layer of acoustic mat on a rigid, stainless steel frame.
283 Damage was estimated based on the wave travel time in undamaged and damaged specimens
284 and calculating the relative elastic modulus:

$$285 \quad D = 1 - \frac{E_t}{E_0} = 1 - \left(\frac{t_0}{t_t}\right)^2 \quad \text{Eq.6}$$

286
287 where E_t is the dynamic elastic modulus after freeze-thaw damage, E_0 is the initial dynamic
288 elastic modulus (before freeze-thaw damage), t_t is the signal transmission time after freeze
289 thaw, and t_0 is the signal transmission time before freeze-thaw damage. In Eq. 6, the change
290 in density of the damaged material is considered negligible.

291

292

293 3.4 Desorption Isotherm

294 3.4.1 Concrete

295 Specimens, with different degrees of damage, were conditioned at [five](#) relative humidities
296 (50%, 65%, 75.3%, 85.1%, and 93.6%). The concrete specimens had an average mass of 52.5
297 g and an average thickness of 5.64 mm. The specimens were cut from the center of cylinder
298 using a precision tile wet-saw [before freeze-thaw loading](#). [The RH values were selected from](#)
299 [standard salt solutions: NaCl₂ \(75.3% RH\), KCl \(85.1% RH\), and KNO₃ \(93.6% RH\)](#)
300 [following the work by Castro \(2011\(b\)\), except for the 50% and 65% RH where](#)
301 [environmental chambers were used to fill intermediate RH values](#). Specimens were
302 conditioned using saturated salt solutions, except for the 50% and 65% RH where
303 environmental chambers were used [to fill intermediate RH values](#). Equilibrium at a given
304 relative humidity was defined as a change in mass less than 1.0 mg in one month. A total of
305 three replicate specimens were used for each degree of damage (a total of 108 samples for all
306 degrees of damage and RH). [The total time required to reach equilibrium for all the samples](#)
307 [and complete all measurements was approximately 9 months. Note that measurements were](#)
308 [performed simultaneously. It was found that the time to reach equilibrium \(regardless of the](#)
309 [RH increment\) was shorter for materials with higher degrees of damage. This may be, in part,](#)
310 [attributed to higher porosity and higher pore connectivity of materials with a higher degrees](#)
311 [of damage](#).

312 3.4.2 Mortar

313 To measure desorption isotherm of mortar specimens with different degrees of damage, an
314 automated sorption analyzer was utilized. Small samples (0.5-1.5 mm thick, weighing 50-100
315 mg) were used; these samples were cut with a precision Scanning Electron Microscope wet-
316 saw operating at 120 rpm with 5g of added mass to ensure the samples were not damaged

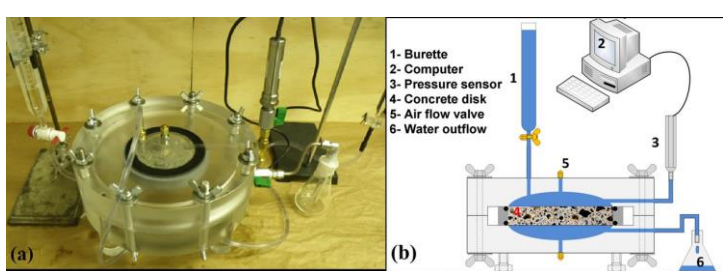
317 | during cutting. [We note that this careful procedure was especially important at high degrees](#)
318 | [of damage, when the material had a degraded strength.](#) These samples, with an average
319 | dimension of approximately 1 mm well represented the bulk material in absorption
320 | simulations. A discussion of the effect of sample size is provided in the Results and
321 | Discussion Section. In the sorption analyzer, mass of the specimens were monitored while the
322 | relative humidity was sequentially dropped from 97.5% to 0% RH, with a 5% RH decrease
323 | between each successive step after reaching equilibrium. Equilibrium was defined as a mass
324 | change less than 0.001 mg within 15 minutes. This criterion was previously developed,
325 | tested, and validated in the comprehensive studies by [Villani et al. \(2012\)](#), [Castro \(2011\(b\)\)](#),
326 | and [Pour-Ghaz et al. \(2010\)](#).

327

328 3.5 Saturated Hydraulic Conductivity

329 The saturated hydraulic conductivity (K_s) measurements were performed using an in-
330 house developed equipment shown in Figure 2. The details of the saturated hydraulic
331 conductivity test can be found in ([Ghasemzadeh and Pour-Ghaz \(2014\)](#)). Measurements were
332 performed on initially saturated 25 mm thick disks. It is important to note that the specimens
333 were never dried. A total of three replicates were used for concrete and a total of four
334 replicates were used for mortar at each degree of damage.

335



336 Figure 2: In-house developed equipment to measure saturated hydraulic conductivity; (a)
337 photograph of equipment, (b) schematic of equipment implementation
338

339 **3.6 Water Sorption**

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

350

351 **3.6 Scanning Electron Microscope**

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

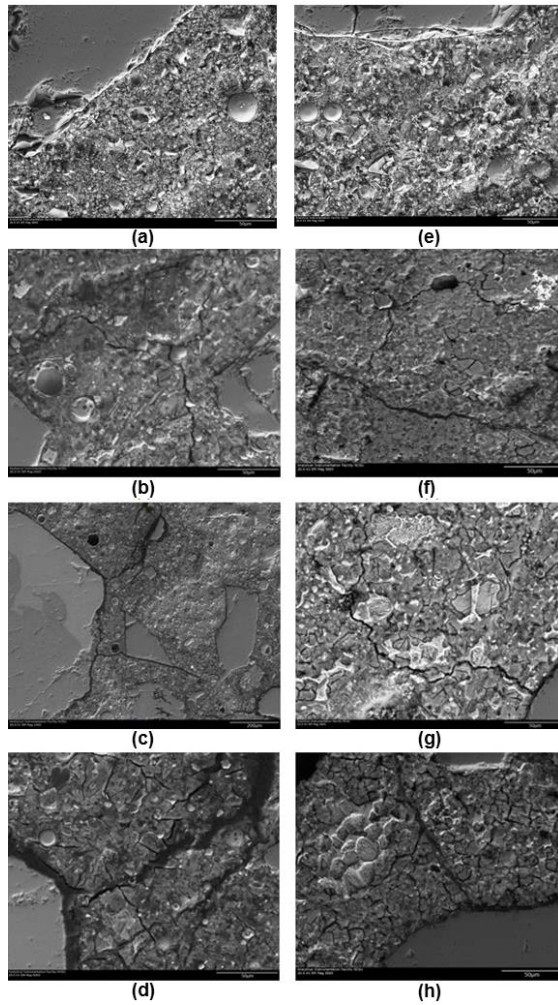
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362 **4. Results and Discussion**

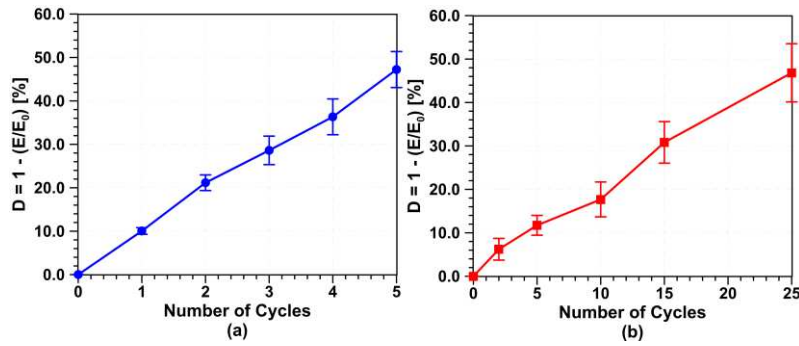
363 **4.1 Freeze-Thaw Damage Visualization and Detection**

364 SEM images for six degrees of damage are shown in Figure 3, the left column shows SEM
365 images of concrete and the right column shows SEM images of mortar. These images are
366 provided to visualize damage in the materials. In the images shown, it is clear that freeze-
367 thaw damage is distributed across the cement paste phase, although some fractures are
368 observed along the aggregate boundaries. As damage increases, the fractures become
369 interconnected and wider in both mortar and concrete. In Figure 3, fracture widths, in all
370 degrees of damage, are below 25 μ m. However, pore sizes, for cement paste in general, range
371 from nanometers to approximately 0.05 μ m (Lura et al. (2003)). The [mortar](#) specimen sizes
372 used in this work for obtaining desorption isotherms are, at a minimum 100-2,500 times
373 larger in dimension than the distributed pore or fracture systems. Consistent with
374 representative volume element ([RVE](#)) size discussed by Nemat-Nasser and Hori (1995), the
375 specimen sizes used for desorption isotherms of mortar are much larger than the
376 microstructure, and therefore, well-represent bulk material properties. [By the same argument,](#)
377 [the use of desorption analyzer was deemed inappropriate for measuring desorption isotherms](#)
378 [of concrete due to the large aggregate sizes. Indeed, the concrete specimens tested here had](#)
379 [aggregates with a maximum size of 19 mm, resulting in a much larger RVE size than mortar.](#)



380
 381 | Figure 3: Representative SEM images of concrete with (a) $D = 0\%$, (b) $D = 21\%$, (c) $D =$
 382 | 29% , (d) $D = 47\%$; and mortar with (e) $D = 0\%$, (f) $D = 18\%$, (g) $D = 30\%$, and (h) $D = 48\%$
 383

384 The damage shown in the material depicted in Figure 3 was quantified using the change in
 385 elastic properties using active acoustic emission methods. In Figure 4, the measured degrees
 386 of damage using active emission for both mortar and concrete are reported. The error bars in
 387 Figure 4 represent standard deviation. The degree of damage in mortar and concrete increases
 388 linearly with the number of freeze-thaw cycles.

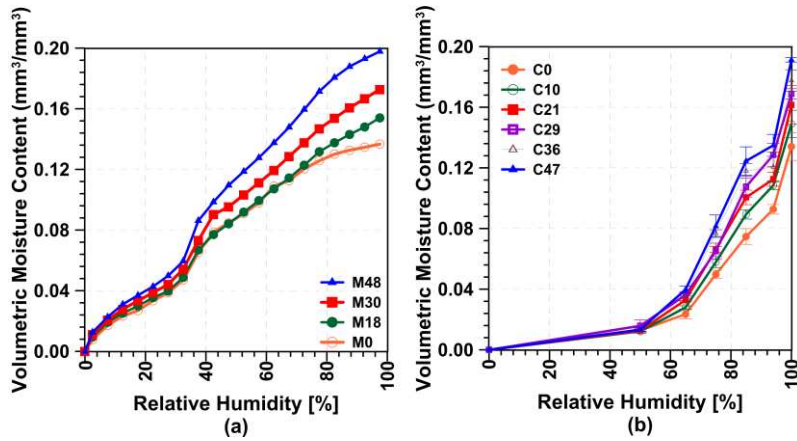


389
 390 Figure 4: Degree of Damage, D (%), based on the reduction of elastic modulus using acoustic
 391 emission; (a) concrete, (b) mortar
 392

393 **4.2 Material Parameters**

394 Figures 5a and 5b show the measured desorption isotherms for mortar and concrete
 395 specimens, respectively. The desorption isotherms of mortar have a higher number of data
 396 points and a wider range of RH values, as compared to that of concrete, since they were
 397 measured using an automated sorption analyzer.

398



399
 400 Figure 5: Desorption isotherm of specimens with different degrees of damage; (a) mortar, (b)
 401 concrete. “M” and “C” denote mortar and concrete, respectively, and the number following
 402 these letters indicate the ~~is the~~ degree of damage (%).
 403

404 For both materials the isotherms shift upward with increased damage, indicating damage
 405 increases porosity over a wide range (Ghasemzadeh and Pour-Ghaz (2014)). The van
 406 Genuchten model (Eq. 4) was fit to these isotherms, after converting them to water retention
 407 curves using Eq. 5. The van Genuchten model parameters for mortar and concrete are
 408 reported in Tables 2 and 3 respectively. The values for saturated hydraulic conductivity (K_s),
 409 saturated moisture content (θ_s), empirical [parameter](#) I , and the rewetting parameters (θ_s^w
 410 and α^w) are also reported in Tables 2 and 3. In Tables 2 and 3 “C” and “M” stand for
 411 concrete and mortar respectively, and the number following these letters indicates the degree
 412 of damage.

413 Table 2: Saturated hydraulic conductivity, saturation water content, and van Genuchten
 414 model parameters for mortar specimens

Identifier	Damage	K_s	α	α^w	n	I	θ_i	θ_s	θ_s^w
-	%	mm/hr	1/mm	1/mm	-	-	-	-	-
M0	0	3.0×10^{-5}	1.2×10^{-2}	2.4×10^{-2}	2.06	-9.0	0.03	0.14	0.10
M18	18	59.0×10^{-5}	1.8×10^{-2}	3.6×10^{-2}	1.75	-8.0	0.01	0.15	0.14
M30	30	194.0×10^{-5}	3.3×10^{-2}	6.6×10^{-2}	1.52	-8.0	0.02	0.17	0.15
M48	48	341.0×10^{-5}	1.7×10^{-2}	3.4×10^{-2}	1.81	-8.0	0.01	0.20	0.17

415

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Table 3: Saturated hydraulic conductivity, saturation water content, and van Genuchten model parameters for concrete specimens

<i>Identifier</i>	<i>Damage</i>	K_s	α	α^w	n	I	θ_i	θ_s	θ_s^w
-	%	mm/hr	1/mm	1/mm	-	-	-	-	-
C0	0	1.4×10^{-4}	6.4×10^{-2}	1.3×10^{-1}	2.26	-7.0	0.03	0.15	0.11
C10	10	7.0×10^{-4}	4.9×10^{-2}	9.8×10^{-2}	2.45	-7.0	0.03	0.15	0.11
C21	21	14.0×10^{-4}	4.6×10^{-2}	9.2×10^{-2}	2.47	-7.0	0.04	0.16	0.11
C29	29	26.0×10^{-4}	4.6×10^{-2}	9.2×10^{-2}	2.48	-6.0	0.03	0.17	0.12
C36	36	56.0×10^{-4}	4.1×10^{-2}	8.2×10^{-2}	2.64	-5.0	0.03	0.18	0.13
C47	47	131.0×10^{-4}	4.3×10^{-2}	8.6×10^{-2}	2.58	-5.0	0.03	0.19	0.14

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We would like to point out here that while Mualem (Mualem (1976)) proposed the parameter I to account for tortuosity and pore connectivity, such a physical interpretation may be only meaningful if $I \geq 0$ in the classical model of unsaturated hydraulic conductivity (Durner 1994). In this study, using the approach described in Section 2.2, satisfactory results were found for negative values similar to the works in (Schneider et al. (2012), Poyet et al. (2011), Schaap and Leij (2000), Yates (1992), and Schuh and Cline (1990)).

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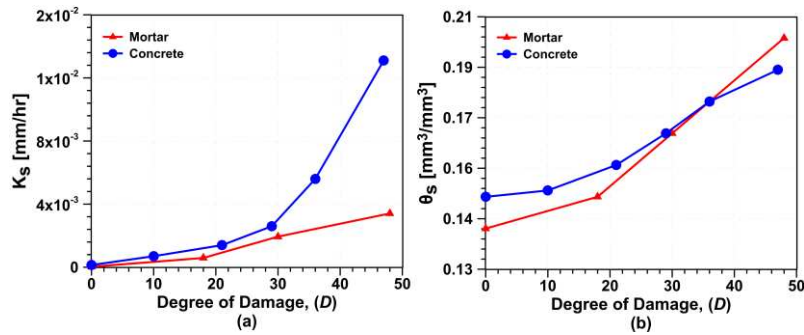
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435

In addition to I , the saturated hydraulic conductivity (K_s) and open porosity (θ_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 6a to increase with the degree of damage in both mortar and concrete. Figure 6b shows that θ_s increases with damage, similar to the increase of porosity observed in desorption isotherms. θ_s (or θ_s^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.



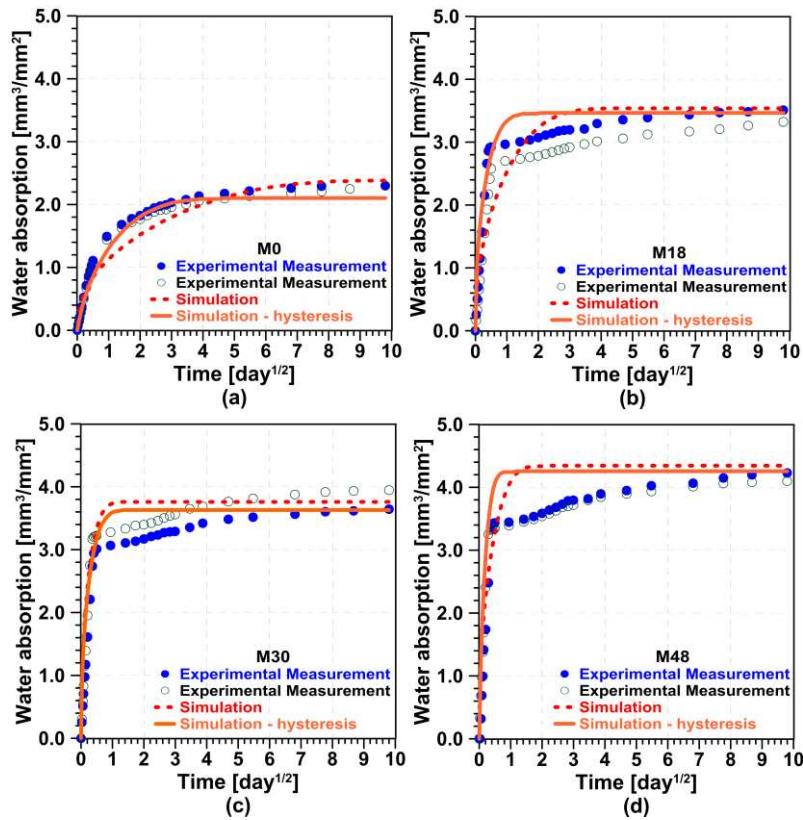
436

437 Figure 6: Effect of damage, D (%), on (a) saturated hydraulic conductivity and, (b) open
 438 porosity, θ_s , in mortar and concrete.

439

440 **4.3 Simulation of Unsaturated Moisture Transport in Mortar**

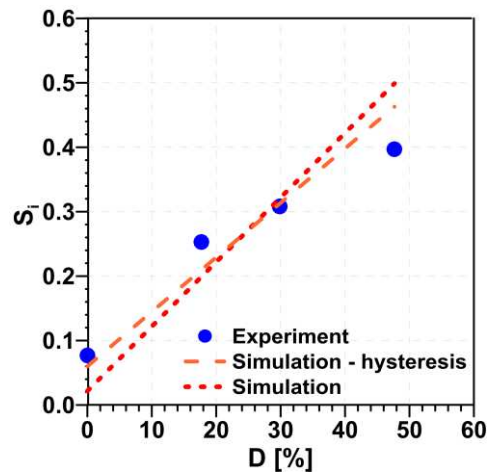
441 Results of the experimental measurements and numerical simulations of water absorption
 442 of mortar with different degrees of damage are compared in Figure 7. Simulations of water
 443 absorption using the material model without hysteresis (from the desorption isotherm) and the
 444 proposed material model including hysteresis are included. The results are presented as
 445 volume of water (mm^3) absorbed per water absorbing surface (mm^2) of the sample versus
 446 square root of time ($\text{day}^{1/2}$). The results were compared for the first 90 days. Note that for
 447 each degree of damage, simulation results are compared with experimental results from two
 448 samples.



449

450 Figure 7: Experimental and numerical sorption results for mortar specimens with different
 451 degrees of damage; a) $D = 0\%$, b) $D = 18\%$, c) $D = 30\%$, d) $D = 48\%$
 452

453 In Figure 7, for all degrees of damage, the results of simulations of water absorption in
 454 mortar compare well with experimental results at early stages of water absorption. In
 455 simulations where hysteresis is considered, early-stage results more closely match
 456 experimental results. The slope of the first linear portion of the experimental and numerical
 457 results, initial sorptivity, is calculated and plotted as a function of degree of damage in Figure
 458 8. Figure 8 confirms that the results of simulation for the initial stages of water absorption
 459 agree well with experimental results, particularly in simulations where hysteresis is
 460 considered.



461
 462 Figure 8: Comparison of experimentally and numerically obtained initial sorptivity, S_i , of
 463 mortar as a function of damage

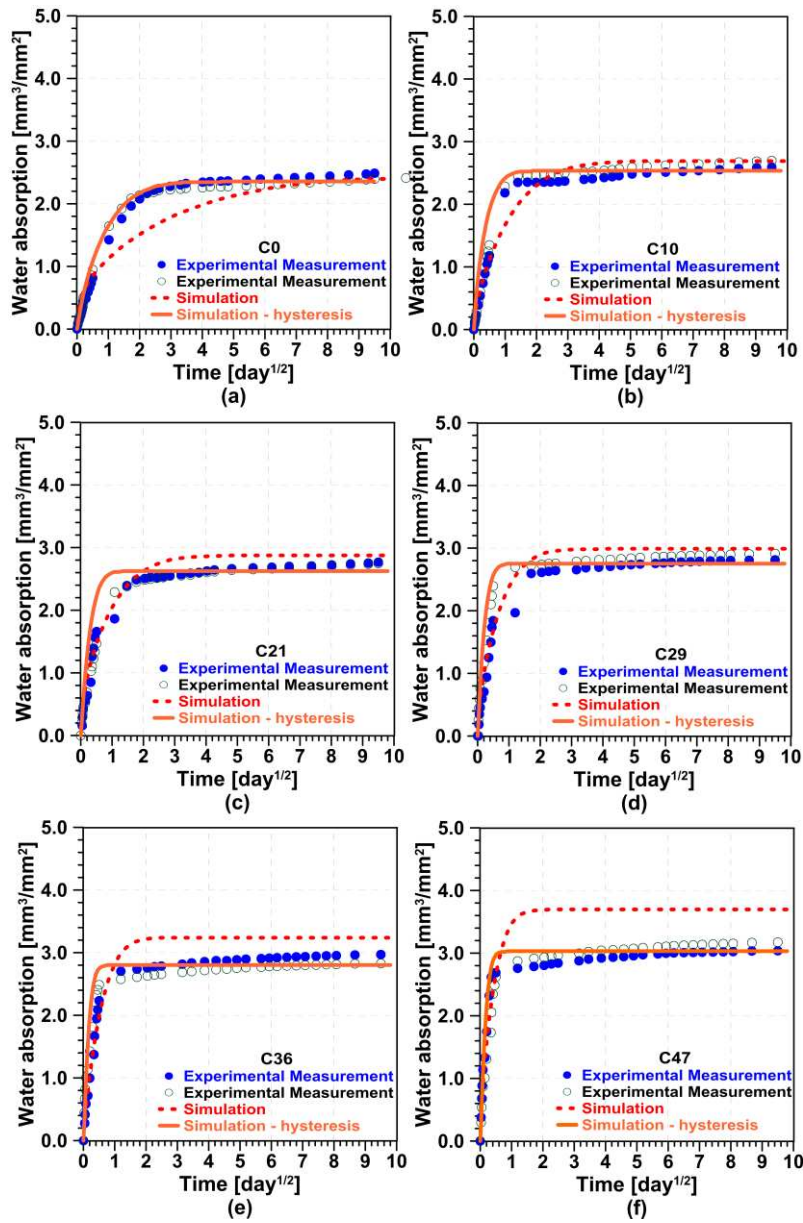
464
 465 In Figure 7, at later stages of water absorption, simulation results deviate from the
 466 experimental results. The deviation increases with damage level. As the damage increases, a
 467 sharp “knee point” appears in both experimental and numerical results. There is, however, a
 468 distinct difference between the numerical and experimental results after the knee point. In
 469 simulated results the sharp transition marks the transition from unsaturated to saturated state
 470 of the sample while in experimental results the specimen continues to absorb water after the
 471 knee point. In experimental results, the knee point marks transition from capillary suction to
 472 air diffusion and dissolution mechanism of water absorption ([Ghasemzadeh et al. \(2016\)](#),
 473 [Ghasemzadeh and Pour-Ghaz \(2014\)](#)). Since Richards’ Equation does not account for air
 474 diffusion and dissolution mechanisms, in simulation results (Figure 7), the specimen
 475 continues to absorb water with capillary suction until saturation ([Li et al. \(2016\)](#)). However,
 476 in experimental results, the specimen continues to absorb water after the knee point, largely
 477 due to the effects of air diffusion and dissolution mechanisms.

478

479 **4.4 Simulation of Unsaturated Moisture Transport in Concrete**

480 Results of the experimental measurements and numerical simulation of water absorption in
481 concrete with different degrees of damage are compared in Figure 9. Simulation results
482 considering hysteresis are also reported. Similar to the results for mortar specimens, the
483 results are compared for the first 90 days. Note that for each degree of damage, simulation
484 results are compared with experimental results from two samples.

485 The results in Figure 9 are similar to the results presented in Figure 7. At early stages of
486 water absorption, the simulation and experimental results agree well while they diverge at
487 later stages of water absorption. Simulations considering moisture hysteresis are shown to
488 more closely match experimental results in both late- and early-stages of moisture. This is
489 largely due to the improved estimation (relative to using drying data) of saturated moisture
490 content after drying.



491

492 Figure 9: Experimental and numerical sorption results for concrete specimens with
 493 different degrees of damage; a) D = 0%, b) D = 10%, c) D = 21%, d) D = 29%, e) D = 36%,
 494 f) D = 47%

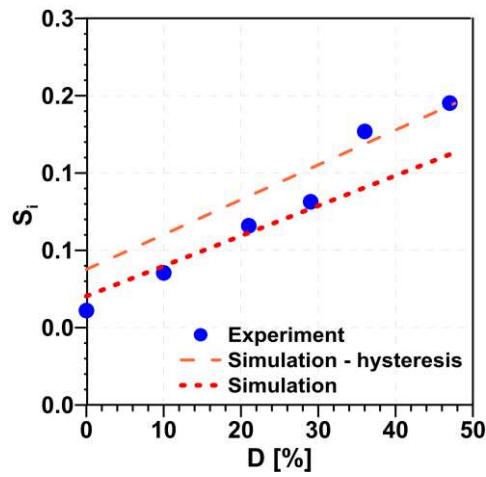
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498 Figure 10, similar to Figure 8, compares the initial sorptivity calculated from experimental
 499 and numerical results. Again, Figure 10 confirms that the results of simulation for the initial
 500 stages of water absorption agree well with experimental results. Considering the effect of
 501 hysteresis in the simulations significantly improves the estimation of initial sorptivity at
 502 higher degrees of damage.

503



504

505 Figure 10: Comparison of experimentally and numerically obtained initial sorptivity, S_i , of
 506 concrete as a function of damage

507

508 4.5 Discussion of Unsaturated Moisture Absorption Modeling Using the Classical 509 Isothermal Model

510

511 Simulation of moisture ingress using Richards' Equation only describes the physics of
 512 capillary suction. For cementitious material with distributed damage, the accuracy of
 513 simulation results is highly dependent on the experimentally obtained isotherms and
 514 hydraulic parameters. In particular, the value of saturated hydraulic conductivity and open
 515 porosity significantly affect the simulation results. The advantages of using the simulation
 516 techniques presented in this paper are (i) the material parameters are directly measured using
 517 well-researched and well-developed experimental techniques, (ii) simulation of moisture

518 absorption using Richards' Equation requires relatively few modeling parameters, and (iii)
519 the material model considering hysteresis does not require the adsorption isotherm – the
520 acquisition of which may require considerable experimental time.

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

533

534 **5. Conclusion**

535 In this work, a classical isothermal unsaturated moisture transport model was used to simulate
536 moisture ingress in mortar and concrete with a wide range of damage. In the material model
537 where hysteresis was not considered, material parameters were obtained from experimental
538 measurements. For the material model accounting for hysteresis, material parameters were
539 developed based off experimental and analytical means. The results indicate that, for all
540 levels of damage, the classical isothermal unsaturated moisture transport model well
541 simulates the early stages of moisture ingress in mortar and concrete where capillary suction
542 is the underlying mechanism. At later stages where air diffusion and dissolution mechanisms

543 as well as matrix-fracture interaction play a more significant role, the results of simulations
544 excluding the effects of hysteresis deviate from experimental measurements. In contrast,
545 results of late-stage water absorption in simulations considering hysteresis more closely
546 match experimental results. The use of more advanced material models might be necessary
547 to obtain more accurate results at later stages of water absorption.

548

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559

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