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A simple practical method for determination of moisture transfer coefficient of mature concrete using a combined experimental-numerical approach

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Abstract. In this paper, a simple practical method is introduced in which a simple weight measurement of concrete and finite element numerical analysis are used to determine the moisture transfer coefficient of concrete with a satisfactory accuracy. Six concrete mixtures with different water-to-cementitious material (w/cm) ratios and two pozzolanic materials including silica fume and zeolite were examined to validate the proposed method. The comparison between the distribution of the moisture content obtained from the model and the one from the experimental data during both the wetting and drying process properly validated the performance of the method. With the proposed method, it was also shown that the concrete moisture transfer coefficient considerably depends on the pore water saturation degree. The use of pozzolanic materials and also lowering w/cm ratio increased the moisture transfer coefficient during the initial sorption, and then, it significantly decreased with an increase in the water saturation degree.

Keywords: moisture transfer coefficient; numerical modeling; silica fume; wetting and drying; zeolite

1. Introduction

The durability-based design of reinforced concrete (RC) structures, especially in marine environments, has become significantly important during the past few decades, and it has been known that the durability of RC constructions mainly depends on the transport of aggressive ions such as chlorides and sulfates in the concrete pores (Sabir *et al.* 1998, Hubert *et al.* 2003, Yoo *et al.* 2011, Dousti *et al.* 2013, Moradian *et al.* 2014, Hallaji *et al.* 2015). In order to predict service life for durability based design of structures, it is required to determine the moisture distribution and the ionic transport of concrete (Yang *et al.* 2006, Samson *et al.* 2008, Shekarchi *et al.* 2010).

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Since moisture moves through concrete pores partially in the form of liquid and partially in the form of vapor state, it is required to select the main variables of the model based on either water saturation degree (*w*) (i.e., fractional volume of voids filled with water) or pore relative humidity (*h*). Several models have been developed to predict the moisture distribution in concrete as well as its variations with time (Sarkar and Bhattacharjee 2014, Ba *et al.* 2014, Zhang *et al.* 2015). Bazant and Najjar (1971, 1972) presented a model based on the water vapor diffusion to approximate the humidity profile in concrete for prediction of shrinkage when concrete is exposed to exterior condition. Some researchers (Martin-Perez 1999, 2000, Nilsson 2002, Aquino *et al.* 2004, Peuhkuri *et al.* 2008) also investigated the moisture distribution in concrete based on the humidity that is often in the drying state and occasionally in the wetting state; however, it has been recognized that during water absorption, moisture moves into the concrete due to the capillary forces rather than the vapor diffusion process (Wanga *et al.* 2001). As a result, it was recommended that moisture distribution in concrete should be determined using pore water instead of humidity profile, especially for the modeling of ions movement in concrete exposed to marine environments. Water flux is one of the main factors that can alter the movement of aggressive ions such as chloride in partially saturated concrete (Janz 1997). Several researchers (Saetta *et al.* 1993, Carpenter *et al.* 1993, Lockington *et al.* 1999, McCarter *et al.* 2001, Ayano and Wittmann 2002, Janz 2002, Ishida *et al.* 2007, Iqbal and Ishida 2009, Qin *et al.* 2009, Lin *et al.* 2010, Conciatori *et al.* 2011, Glouannec and Salagnac 2012) attempted to predict the moisture distribution in concrete under wetting and drying condition with water saturation degree.

Moisture transfer coefficient (m^2/s) is the most important parameter in the prediction of water either and humidity distribution profiles in concrete; therefore, a reliable test method is required to determine this parameter. Determination of either *w* or *h* profile in concrete exposed to the wetting and drying was generally used to approximate the moisture transfer coefficient of concrete. Peuhkuri *et al.* (2008) and West and Holmes (2001) used humidity probes embedded along the direction of the moisture flux at distances of 20 mm and 25 mm to determine the humidity profile; the technique was quite complex and costly. McCarter *et al.* (2001) also determined the humidity profile using a humidity probe; however, they encountered some technical problems with the measurement of humidity in their concrete samples since there was a delay in the equilibrium state between the humidity probe and the surrounding concrete at the time of the measurements. The pore water content at any depth of a concrete specimen subjected to the wetting and drying can also be determined using slice-dry-weight method. In this method, the concrete specimen is rapidly sliced into discs, weighed, dried, and weighed again to determine the water content profile of concrete. The moisture transfer coefficient of concrete can be calculated using the water content profile of concrete. In this destructive method, one specimen is destroyed every time when the moisture profile is determined (McCarter *et al.* 2001).

Since determination of moisture transfer coefficient using profile methods is expensive and associated with some inherent errors, some initial efforts were made by Samson *et al.* (2008) to determine this parameter with the measurement of mass change in concrete. They only evaluated this method for determination of moisture transfer coefficient in drying state during moisture loss process using a one-dimensional finite element analysis.

In this work, the application of the mass change method in determination of moisture transfer coefficient in both wetting and drying states is demonstrated. A three-dimensional finite element technique is used to fit the experimental data to the governing equations of moisture transfer and hence, determination of moisture transfer coefficient. Six concrete mixtures with different w/cm and pozzolanic materials including silica fume and zeolite were tested to evaluate the proposed

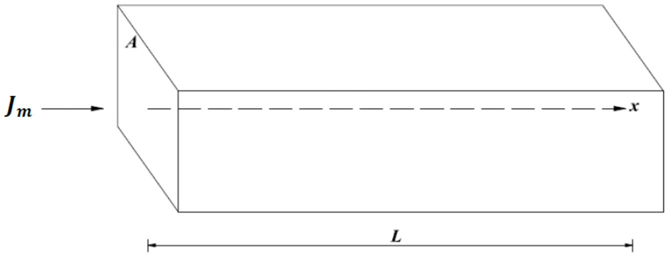


Fig. 1 Typical 1-D model for moisture transfer into concrete

method. The method is also verified with the test results reported by other researchers.

2. Theoretical background

Concrete is a porous material which allows the moisture transports through its pores. In the last few decades, several theories have been developed mostly based on the mass, momentum, and energy conservations expressed by Darcy's Law and Fick's Second Law of diffusion. These theories explain the liquid transfer or vapor diffusion through a porous matrix (Nguyen *et al.* 2008, Baroghel-Bouny *et al.* 2001). The liquid phase contains free and physically bound water, and the gas phase is a mixture of air and water vapor (Glouannec and Salagnac 2012). The total moisture flux, $\boldsymbol{J_m}$ (m/s), which can be transported either as water vapor flow, $\boldsymbol{J_v}$ (m/s), or as liquid water flow, $\boldsymbol{J_l}$ (m/s), or as a combination of these two phases (Fig. 1), can generally be expressed as (Nilsson 2002, Peuhkuri *et al.* 2008)

$$\boldsymbol{J_m} = \boldsymbol{J_v} + \boldsymbol{J_l} \tag{1}$$

The vapor movement is less sensitive to capillarity suction (Saetta *et al.* 1993, Conciatori *et al.* 2008) and thus the vapor flux, which is governed by the vapor pressure in unsaturated pore space, can be described by the isothermal vapor transport coefficient, D_v (m^2/s) (Glouannec and Salagnac 2012). In addition, $\boldsymbol{J_v}$ is the moisture flux due to isothermal vapor diffusion resulted from the vapor concentration gradient. For most porous materials such as concrete, the use of relative humidity gradient, ($\boldsymbol{\nabla h}$), as the driving force, is practically equivalent to using moisture content. Therefore, some researchers (Xi *et al.* 1994a, McCarter *et al.* 2001, Hoseini *et al.* 2009) used the pore relative humidity (h) as a field variable such that:

$$\boldsymbol{J_v} = -D_v \boldsymbol{\nabla h} \tag{2}$$

Transport of liquids in porous media such as concrete generally occurs in open pores due to diffusion, suction, permeation, and capillary absorption (Bazant and Najjar 1971, Hall and Hoff 2011). The mechanism can be expressed by Darcy's law (Bazant and Najjar 1972). The driving forces of the diffusion and suction processes in unsaturated concrete are concentration and pressure gradients, respectively. The capillary absorption is driven by surface tension (Hanzic *et al.* 2010), which increases with a decrease in pore radius (Kim and Lee 1998). Although the described water transport is due to the capillary potential gradient and not strictly due to the diffusion process, it has been shown that diffusion form of the governing differential equation on water transport can be described as follows (Carpenter *et al.* 1993, Claisse *et al.* 1997)

$$\boldsymbol{J_l} = -D_l \boldsymbol{\nabla w} \tag{3}$$

where w and D_l represent pore water saturation degree and liquid water diffusion coefficient (m^2/s), respectively.

The rate of moisture transfer into concrete is not the same for the moisture gain and moisture loss. The moisture movement during the drying process is considered solely as a vapor diffusive process (Janssen *et al.* 2007, Lin *et al.* 2010). It is also known that the major cause of water flow into a porous medium, during the moisture absorption, is the pressure gradient and/or capillary forces (Janssen *et al.* 2008), and it should be therefore considered as a liquid form of moisture transport. Depending on the dominant mechanism during water transport, the moisture movement can be expressed in two ways: either in the form of the pore evaporable water (i.e., free water content) (w), or in the form of pore relative humidity (h) (Bazant and Najjar 1972). Vapor and liquid flow in the same direction and cannot be easily separated in an experiment. Thus, for isothermal cases, a description of the total moisture flow ($\boldsymbol{J_m}$) for both vapor and liquid can generally be simplified by only one equation (Martys and Ferraris 1997, Martin-Perez 1999, Maekawa *et al.* 2003)

$$\boldsymbol{J_m} = \boldsymbol{J_l} + \boldsymbol{J_v} = -D_l \boldsymbol{\nabla w} - D_v \boldsymbol{\nabla h} \quad \approx \begin{cases} \boldsymbol{J_m} = -D_w \boldsymbol{\nabla w} \\ \boldsymbol{J_m} = -D_h \nabla h \end{cases} \tag{4}$$

where D_w and D_h are the equivalent total moisture transfer coefficients (m^2/s) in the form of liquid and vapor, respectively. D_w and D_h have different physical meanings with different values for a given moisture flux and are a function of pore water saturation degree and relative humidity of pores, respectively (Xi *et al.* 1994a). However, it is usually more practical to use one mechanism of moisture transfer, preferably water movement, in both states of water absorption and moisture loss, especially for the modeling of ions transfer (Martin-Perez 2001). Therefore, by eliminating the effect of gravity and considering the mass conservation of water in the concrete pores, conductivity, pore-structure development, and moisture loss due to hydration (Iqbal and Ishida 2009), the rate of moisture transfer per unit area in a certain direction is proportional to the gradient of the moisture concentration in that direction. Thus, the water saturation degree of cement paste or concrete (w) should satisfy the following partial differential equation (Crank 1975, Martys and Ferraris 1997)

$$\frac{\partial w}{\partial t} + \nabla.(\boldsymbol{J_m}) - Q_w = 0 \tag{5}$$

where Q_w denotes sink term of evaporable water due to hydration or other chemical reactions. Assuming no chemical reaction between water and the solid phase of pore structure, a constant solution density, and isothermal condition used in this study, the substitution of Eq. (4) into (5) yields (Wang and Fang 1988, Akita *et al.* 1997)

$$\frac{\partial w}{\partial t} = -\nabla.(\boldsymbol{J_m}) = D_w \nabla^2 w \tag{6}$$

The major problem in accurate determination of D_w is that moisture movement through cementitious materials depends considerably on the pore moisture content. Some empirical correlations have been proposed to give an approximation of D_w during moisture gain (Navarri and Andrieu 1993, Dietl *et al.* 1998, Buchwald 2000, Aquino *et al.* 2004) or during moisture loss (Xi *et al.* 1994a ,b, Martys and Ferraris 1997, Ayano and Wittmann 2002, Janz 2002, Kodikara and Chakrabarti 2005, Lin *et al.* 2010, Idiart *et al.* 2011). Among the proposed correlations, Eqs. (7)-(8) are the most common equations for modeling the variation of D_w with the w of pores in the wetting and drying process, respectively.

$$D_w = D_w^d e^{-\beta w} \tag{7}$$

$$D_w = D_w^s \left[\alpha + \frac{1-\alpha}{1+\left(\frac{1-w}{1-w_{cr}}\right)^N} \right] \tag{8}$$

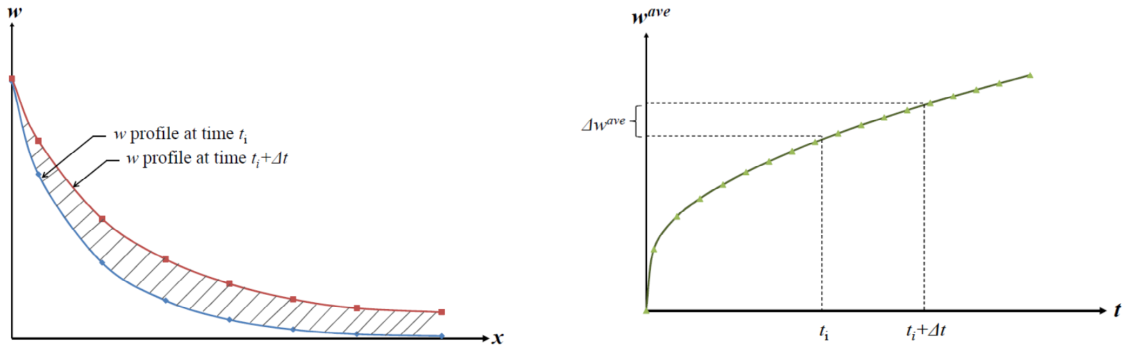
where D_w^d and D_w^s are dried state moisture transfer coefficients during moisture absorption and saturated state moisture transfer coefficients, when the exposed surface is subjected to drying, respectively. β, α, w_{cr} and N are model parameters which need to be determined.

In Eq. (7) when material absorbs water, D_w decreases during the wetting process. However, in Eq. (8), during the drying state, D_w reduces with a decrease in w. Therefore, it can be generally stated that D_w diminishes during both the wetting and drying processes of concrete.

3. Proposed approach

Distribution of water in concrete due to the moisture flux, $\boldsymbol{J_m}$, at time t_i can be shown with a curve plotted in Fig. 2(a) when moisture ingress into concrete from only one side of the specimen (i.e., unidirectional moisture ingress condition as shown in Fig. 1). If the water saturation degree w is obtained at several points along the concrete depth using the slice-dry-weight method, the moisture transfer coefficient D_w can be approximated by fitting the Fick's second law of diffusion to the experimental data using Eq. (6).

In practice, this method is not only difficult and costly, but also does not guarantee an acceptable level of accuracy because of inherent errors associated with the slice-dry-weight method. As an alternative approach, in this study a simple mass change method was used to numerically obtain the moisture transfer coefficient of concrete. In this method, w^{ave} at time t_i



(a) Moisture profile at specified times

(b) Average water saturation degree in total pores over time

Fig. 2 Typical w^{ave} and w distribution profiles in concrete was calculated from the area under the curve of water saturation profile (Fig. 2(a)). The difference between $w^{ave}(\text{at } t = t_i)$ and $w^{ave}(\text{at } t = t_i + \Delta t)$ is a definite value as shown in Fig. 2(b).

The value of $\Delta w^{ave}(t)$ was measured experimentally in water absorption or moisture loss tests as a function of time. Using the governing differential equation of moisture transfer (Eq. (6)), the experimental results of $w^{ave}(t)$ were fitted to the numerical results obtained from the finite element method and therefore, the moisture transfer coefficient of concrete was determined.

4. Numerical modeling

4.1 Finite Element (FE) formulation

A closed-form solution of Eq. (6) is not possible due to the dependency of material properties and boundary conditions on the physical characteristics of concrete at various exposure times (Janz 2002). Among various methods available to solve these equations, the residual weight (Galerkin) method was employed to solve the equation using the finite element technique. Applying the Galerkin weighted residual method on Eq. (6) yields

$$[K_1 + K_2]\{w_i\} + [C]\{\dot{w}_i\} = \{f\} \tag{9}$$

where,

$$[K_1] = D_w \int_V [B]^T [B] dv \tag{10}$$

$$[K_2] = B_w \int_\Omega \{N_i\}^T d\Omega \tag{11}$$

$$[C] = \int_V \{N_i\}^T \{N_i\} dv \tag{12}$$

$$\{f\} = B_w \int_\Omega \{N_i\}^T \{w_{env}\} d\Omega \tag{13}$$

and N_i, Ω and V are the shape function, boundary and main domain, respectively and $[B]$ equals to $\nabla\{N_i\}$. i is the number of shape function which varies from 1 to 8 for eight nodes three-dimensional element. Note that $[K_2]$ and $\{f\}$ are only considered at element boundaries. Eq. (9) is integrated over time using a finite difference approximation (Prazak *et al.* 1990, Martin-Perez 1999).

4.2 Boundary conditions

The moisture transfer from the external environment to the concrete surface (wetting) or vice versa (drying) has been studied by Saetta *et al.* (1993) and Akita *et al.* (1997). They showed that the moisture transfer at concrete boundary is defined as:

$$J_m^n = B_w(w_{sur} - w_{env}) \tag{14}$$

where J_m^n is the moisture flux normal to the concrete surface (m/s), B_w is the surface moisture transfer coefficient (m/s) (Saetta *et al.* 1993) or emissivity coefficient (Kodikara and Chakrabarti 2005), w_{sur} and w_{env} are w at the surface of concrete and the equivalent w in the surrounding environment in terms of the relative humidity, respectively. w_{env} is 1.0 when concrete is exposed to water and is equal to the value estimated in relation to the desorption isotherm during the moisture loss. The isothermal desorption of the cement binder is experimentally obtained by measuring the moisture content of the cement paste in equilibrium with different ambient relative humidity levels at the temperature of 20°C (McCarter 1993). At each ambient relative humidity level, a desorption isotherm indicates the corresponding moisture content value at a given constant temperature. The most widely used adsorption equation is the Brunauer-Emmett-Teller (BET) equation (Brunauer *et al.* 1938). The relationship between pore relative moisture content and relative humidity is complex and nonlinear which is described as follows (Bazant and Najjar 1972)

$$w_{env} = \frac{(1-k)[1+(C-1)k]h_{env}}{(1-kh_{env})[1+(C-1)kh_{env}]} \tag{15}$$

wherein,

$$C = e^{\frac{855}{T}} \tag{16}$$

$$k = \frac{\left(1-\frac{1}{n}\right)C-1}{C-1} \quad 0 < k < 1 \tag{17}$$

$$n = \left(2.5 + \frac{15}{t_e}\right)(0.33 + 2.2w/cm) \quad if \quad t_e > 5\; days\; and\; 0.3 < w/cm < 0.6 \tag{18}$$

and h_{env}, T and t_e are environmental relative humidity, concrete temperature (°*K*), and equivalent hydration age (day), respectively.

B_w is calculated using the equivalent thickness (l_e) of the concrete adjacent to the real exposed surface from $B_w = D_w/l_e$. By comparing analytical results with experimental ones, Bazant and Najjar (1972) reported that the value of the equivalent surface thickness is around 0.75 mm; thus, the value of B_w is defined as $B_w = [D_w(m^2/s)]/[0.75 \times 10^{-3}\,(m)]$.

4.3 Computer based model

In this study, using the moisture transport finite element formulation of the governing equation during the wetting and drying process, a 3-D finite element model was developed by ANSYS 5.4 software to numerically solve the moisture transport equation in space as a boundary-value problem and in time as an initial-value problem. Since the wetting and drying processes affect all six faces of concrete specimens, it was necessary to consider the moisture flux to all faces of the specimen as the boundary condition. The concrete material was assumed isotropic and hydration was also neglected over the course of the experiments as the age of concrete samples were quite high. With respect to the above mentioned points, the flowchart for modeling the water absorption

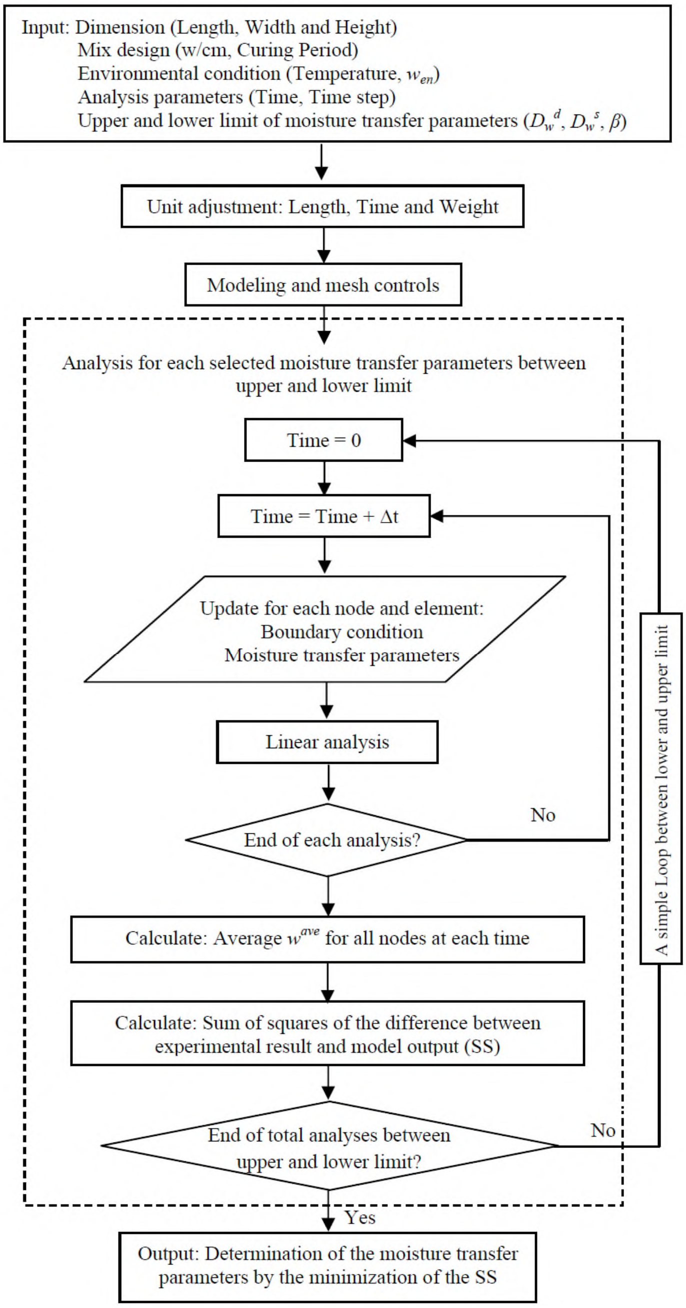
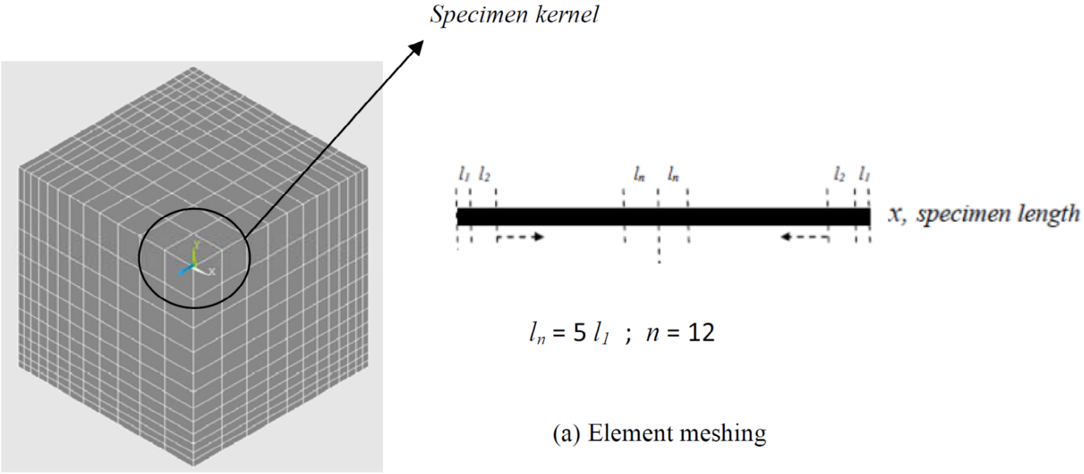


Fig. 3 A flowchart showing the algorithm used in the numerical model

and moisture loss process is shown in Fig. 3. Also, the finite element meshing and time steps of analysis are illustrated in Figs. 4(a)-(b), respectively. Model input parameters are shown in Table 1. D_w was approximated by fitting the data output resulted from the presented model, to the test results obtained using the least-square method.



Note: $^1/_8$ concrete specimen was selected to analysis.

(a) Element meshing

Wetting period				
t	0-2 h	2-8 h	8-30 h	30-200 h
Δt	0.125 h	0.5 h	2 h	20 h

Drying period				
t	0-5 h	5-30 h	30-100 h	100-1000 h
Δt	1 h	5 h	10 h	50 h

(b) Time steps of FE analysis

Fig. 4 Details of the 3-D FE model

Table 1 Model parameters

Input Variables		
Parameters	Wetting	Drying
B_w	D_w (m^2/s) in exposed surface /0.75 (mm)	
$w\ (t=0)$	0.0	1.0
w_{env}	1.0	0.36 (w/cm=0.40) 0.34 (w/cm=0.45) 0.31 (w/cm=0.50) 0.29 (w/cm=0.55)
Unknown Variables		
Variable	Wetting	Drying
D_w^d	TBD	NA
β	TBD	NA
D_w^s	NA	TBD
α	NA	TBD
N	NA	TBD
w_{cr}	NA	TBD

NA: Not Applicable; TBD: To Be Determined

Table 2 Chemical composition of cementitious materials

Composition (wt. %)	Cement type II	Silica fume	Zeolite
CaO	63.8	3.1	3.8
SiO_2	24.4	86.2	63.1
Al_2O_3	3.8	1.4	11.0
Fe_2O_3	3.1	0.2	0.4
SO_3	1.5	0.3	0.1
MgO	4.4	1.3	1.6
K_2O	0.79	-	-
Na_2O	0.08	-	-
LOI^*	1.1	1.2	8.5
IR^{**}	0.32	-	-
C_3S	55	-	-
C_2S	23	-	-
C_3A	5	-	-
C_4AF	9	-	-

* *LOI*: Loss Of Ignition

** *IR*: Insoluble Residue

5. Experimental program

The major difficulty in establishing reliable moisture transfer parameters is that moisture movement through cementitious materials is basically controlled by the microstructure of the material and especially by the pore size distribution (Kim and Lee 1998, Wanga and Ueda 2011). Therefore, all of the parameters, such as the w/cm ratio and type of supplementary materials, which affect the formation of the microstructure in cementitious materials, have significant impacts on the moisture movement (Bazant and Najjar 1971). Six concrete mixtures were prepared in order to validate the method proposed for the approximation of moisture transfer coefficient (D_w), and to evaluate the influence of mixture proportion on the rate of water absorption and moisture loss. Two types of pozzolanic materials including silica fume (SF) and zeolite (Z) were used. The w/cm ratios varied between 0.40 and 0.55.

5.1 Materials and mixture proportion design

Mixture proportions were designed in accordance with ACI 211.1R. All the materials met applicable ASTM standards. The chemical analysis of cementitious materials is presented in Table 2. Fine and coarse aggregates were prepared from siliceous-calcareous riverbed aggregate with saturated surface dried (SSD) specific gravity and water absorption of 2.55 and 2.8% for the fine aggregate and 2.57 and 1.6% for the coarse aggregate, respectively.

Mixture constituents of all proportions as well as the fresh and hardened properties of the concrete are presented in Tables 3-4, respectively. The slump of fresh concrete was maintained in the range of 10.0±2.5 cm by using an appropriate dosage of polycarboxylate-ether based super-plasticizer, except for W50 and W55 mixes. In these two mixes, high slump values were obtained

Table 3 Concrete mixture proportions

Code	W40	W45	W50	W55	SF7.5	Z10
Cement (kg/m^3)	350	350	350	350	324	315
Silica fume (kg/m^3)	-	-	-	-	26	-
Zeolite (kg/m^3)	-	-	-	-	-	35
Water (kg/m^3)	140	158	175	193	158	158
w/cm	0.40	0.45	0.50	0.55	0.45	0.45
Fine aggregate* (kg/m^3)	956	936	913	890	936	936
Coarse aggregate* (D_{max}=19 mm) (kg/m^3)	884	864	842	821	864	864
Super-plasticizer (kg/m^3)	0.70	0.28	-	-	1.19	1.05

* Aggregate was saturated surface dry

Table 4 Fresh and hardened concrete test results

Code	W40	W45	W50	W55	SF7.5	Z10
Slump (cm)	11.0	12.0	16.0	22.0	12.0	10.5
Air content (%)	3.0	3.2	3.2	3.3	2.2	3.4
Compressive strength (MPa)						
7 days	30.4	28.0	22.4	17.3	31.0	25.9
28 days	42.7	39.1	34.1	31.1	47.4	39.2
90 days	49.0	44.6	40.3	35.2	52.1	44.7
1 year	51.0	48.9	45.4	41.3	58.6	52.2

without super-plasticizer because of the high w/cm of the mixtures.

7.5% and 10% of the weight of cement in mixes SF7.5 and Z10 were replaced by silica fume and zeolite, respectively. Due to the slump drop induced by the addition of silica fume and zeolite in the mixtures, higher dosages of super-plasticizer were used to compensate for the drop of slump.

5.2 Specimen preparation and testing methods

Concrete mixes were prepared and molded in the laboratory condition in accordance with ASTM C192. In this investigation, 15 cm cubic specimens were molded for measuring the water absorption and moisture loss at different time periods.

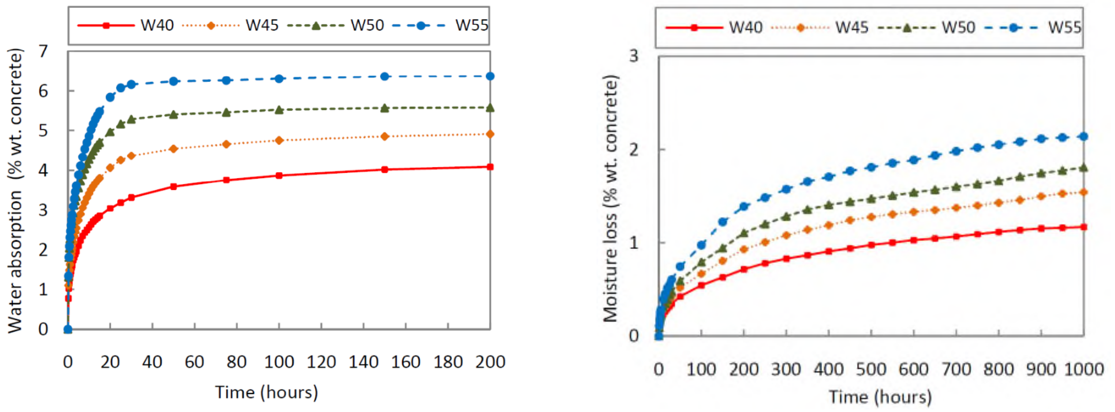
In order to minimize the effect of hydration on the results of water absorption and moisture loss tests, especially for Mix Z10 with a lower hydration rate, the specimens were cured for one year in lime water with a temperature of 23±2ºC. Since the surface absorption characteristics are influenced by casting procedures (McCarter 1993), all surfaces of the specimens were wet cut to make the condition of side surfaces similar. Two series of cubic cut specimens with dimensions of 7.5 cm and 12.5 cm were prepared.

All specimens were oven dried to a constant mass at a temperature of 110±5ºC and then cooled in a desiccator to the temperature of 23±2ºC. The drying condition of the specimens was inspected by comparing weight of the dried specimens at a temperature of 110±5 ºC with the cooled specimens at a temperature of 23±2 ºC. The difference was negligible in all cases; thus there was no moisture gain or loss occurred during the cooling period. Thereafter, specimens were immersed in water at the temperature of 23±2ºC and the specimens were weighed at specified time periods until the time that sample reached its saturated state. Saturated specimens were then exposed to a controlled environment with the relative humidity of 30±2% and temperature of 23±2°C, and the weight of the specimens were measured to monitor the moisture loss over time. The average pore water saturation degree (w^{ave}) was calculated from the amount of water present in concrete divided by the total amount of water required to saturate a dried specimen.

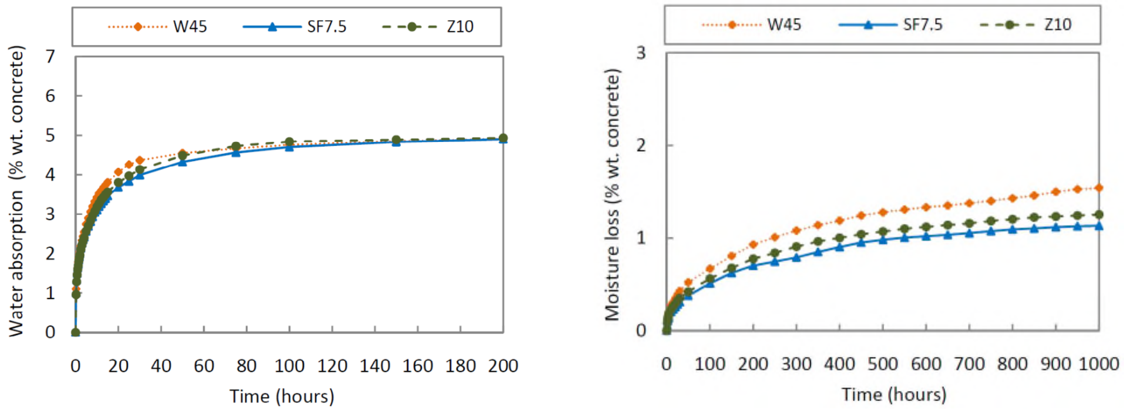
In this study, all the six sides of the specimens were exposed to a controlled environment in order to increase the exposed surface to volume ratio of the specimens. This would increase the accuracy of the test results, because the relative mass change over time due to moisture gain or loss would increase during the wetting or drying process.

6. Results and discussion

The pore water saturation degree (w) depends on the pore characteristics while the total water content variation is influenced by both the pore water saturation degree (w) and the total volume of

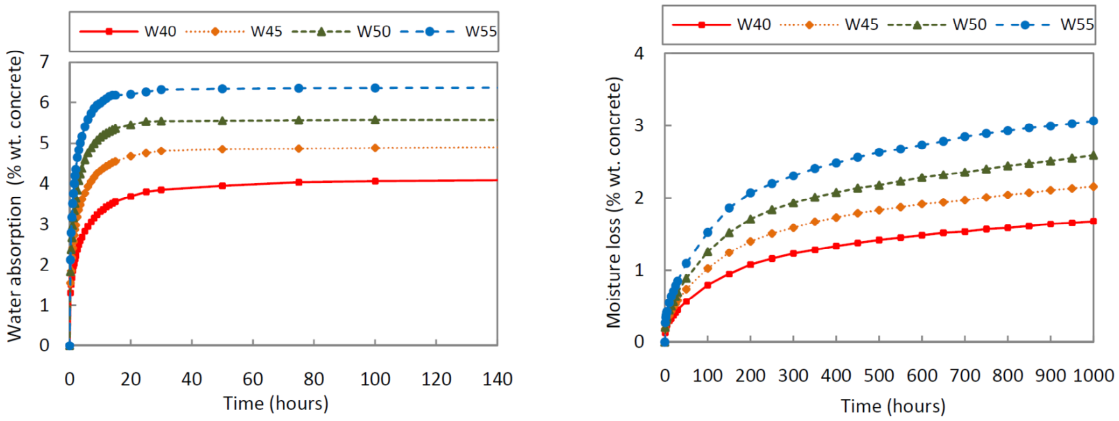


(a) Water absorption of mixes with various w/cm (c) Moisture loss of mixes with various w/cm

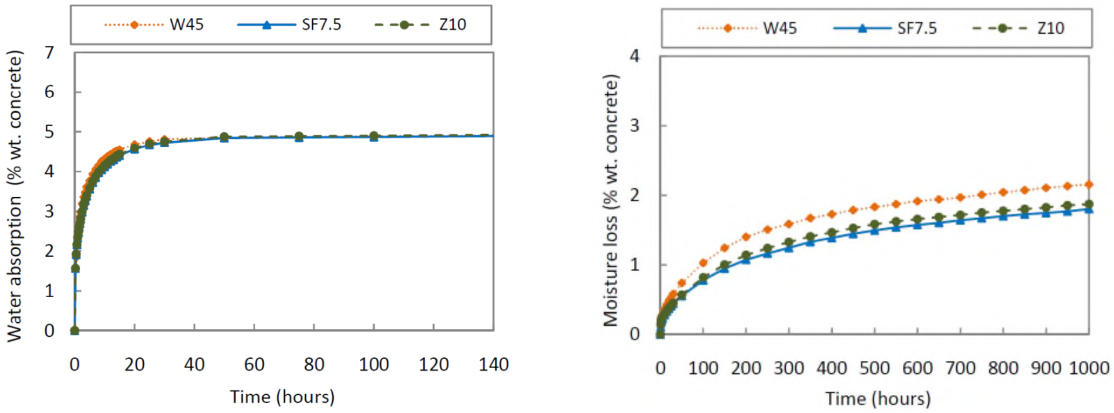


(b) Water absorption of mixes containing pozzolan (d) Moisture loss of mixes containing pozzolan

Fig. 5 Water absorption and moisture loss of 12.5 cm cubic specimens over time



(a) Water absorption of mixes with various w/cm (c) Moisture loss of mixes with various w/cm



(b) Water absorption of mixes containing pozzolan (d) Moisture loss of mixes containing pozzolan

Fig. 6 Water absorption and moisture loss of 7.5 cm cubic specimens over time

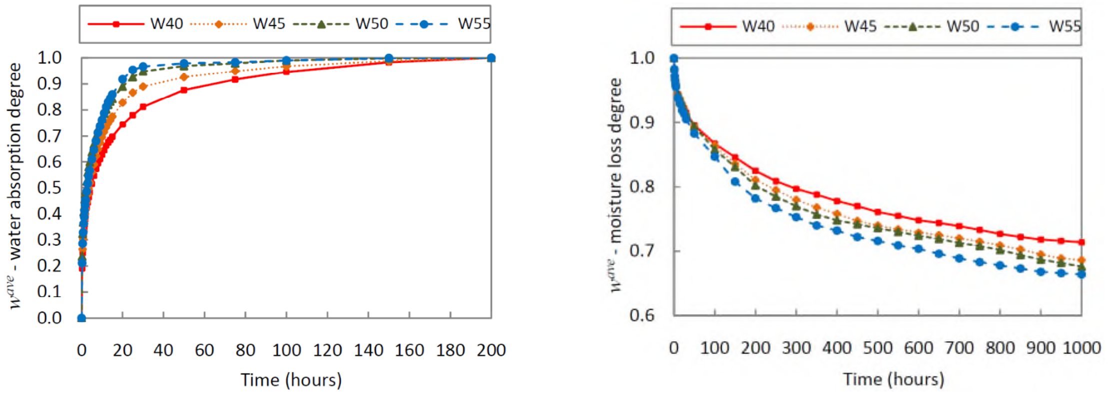
capillary pores. Various factors influencing *w* can be investigated during the wetting or drying processes using the numerical model developed for the calculation of the moisture transfer coefficient. Therefore, in this study, water absorption and moisture loss test results are presented by both the total water absorption and moisture loss and the average water saturation degree of the specimens (w^{ave}).

6.1 Experimental test results

To present the variation of total evaporable water during wetting and drying, typical plots of the total water absorption and moisture loss versus time are shown in Figs. 5-6. These plots illustrate the total water absorption and moisture loss of specimens subjected to water and the surrounding environment, respectively. In general, with the increase of w/cm the total water absorption and moisture loss increase over time. In addition, the amounts of water absorption and moisture loss are greater in the mixes with a higher w/cm because of the larger porosity.

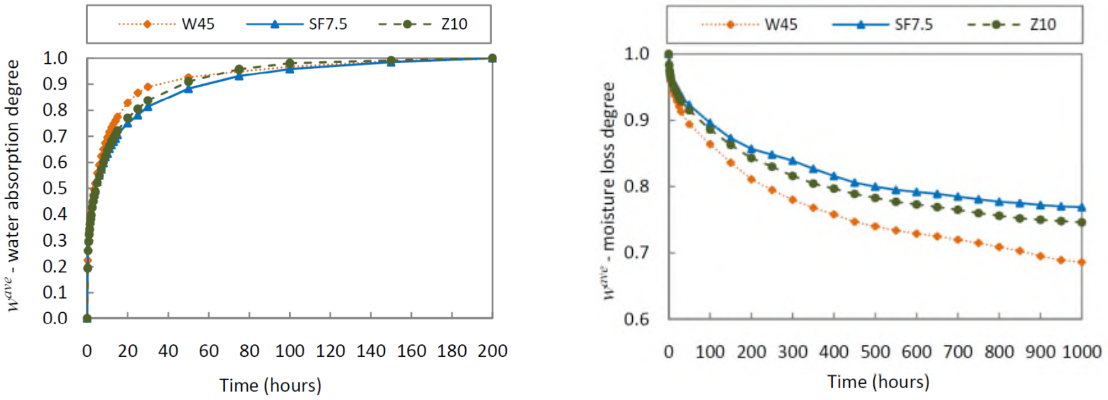
The replacement of a portion of cement by silica fume or zeolite decreases the rate of water absorption and moisture loss (Figs. 5(b), 5(d), 6(b) and 6(d)). This is due to the pozzolanic reactions and filler effect, which render the pore structure of the concrete to a denser and more homogeneous matrix by decreasing the number of large pores while the total porosity remains relatively unaffected (Ahmadi and Shekarchi 2010). This effect is more considerable in concrete made by silica fume compared to zeolite (Valipour *et al.* 2013).

Comparing the absorption rate and the moisture loss rate in Figs. 7-8 it can be clearly observed that the absorption rate is faster than the rate of moisture loss. The dried concrete specimens absorbed more than 70 percent of the water needed for their saturation before one-day of immersion, while only 20 percent of evaporable water of concrete was released after 10 days of exposure to the environment. In addition, nearly 70 percent of the remaining moisture in the concrete pores was not released from the concrete specimens even after 40 days. As mentioned in Section 2, this observation is related to the differences in dominant mechanisms of sorption and desorption, which make the moisture gain rate faster than the moisture loss rate. Since the moisture transfer rate was slow in the drying state, measurements of moisture loss continued for 1,000 hours. At 6 and 12 months, the loss of moisture from specimens was also measured to validate the accuracy of the method as described in Section 5.2.



(a) Water saturation degree of mixes with various w/cm during water absorption

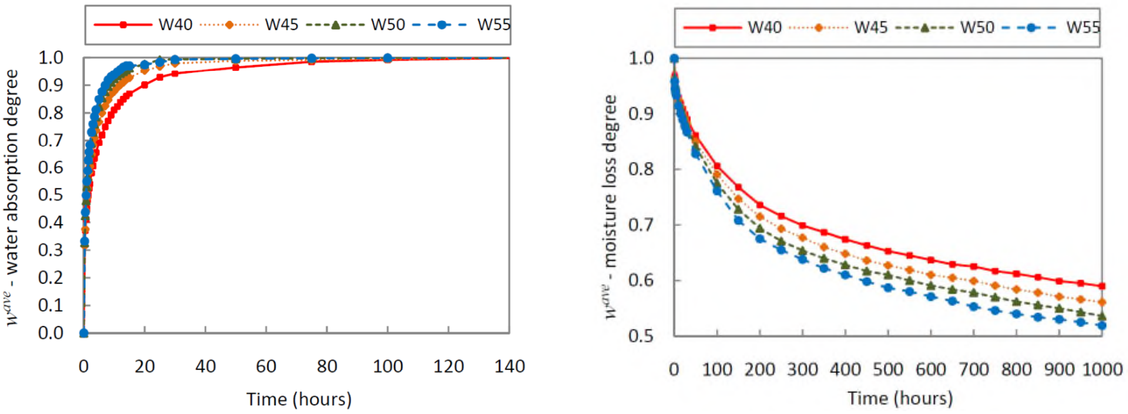
(c) Water saturation degree of mixes with various w/cm during moisture loss



(b) Water saturation degree of mixes containing pozzolan during water absorption

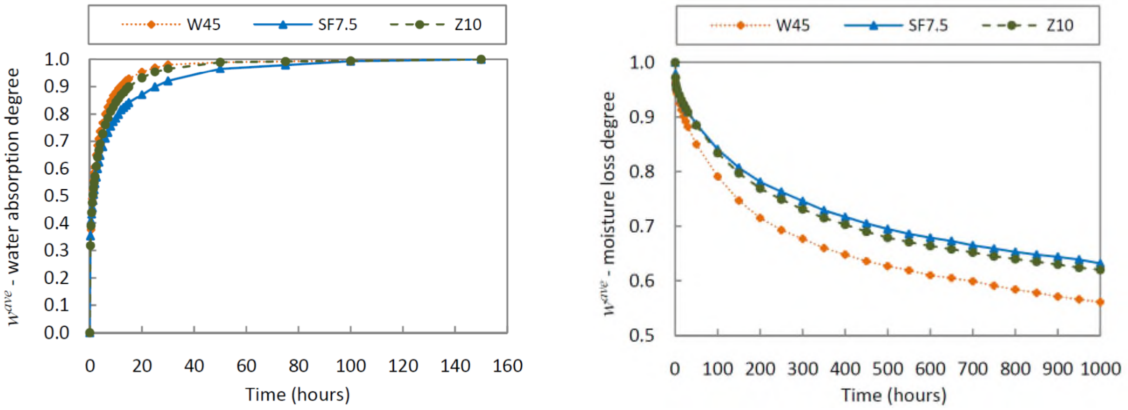
(d) Water saturation degree of mixes containing pozzolan during moisture loss

Fig. 7 Average water saturation degree (w^{ave}) of 12.5 cm cubic specimens during water absorption and moisture loss



(a) Water saturation degree of mixes with various w/cm during water absorption

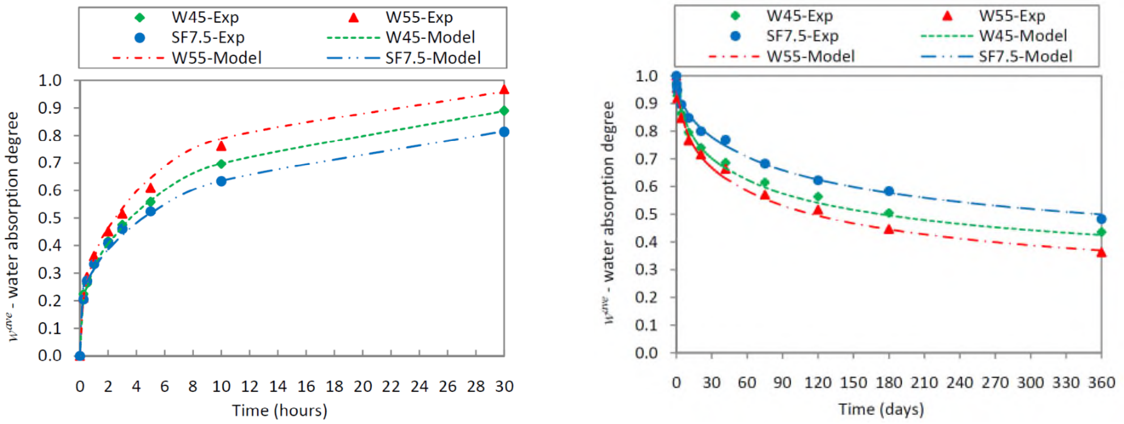
(c) Water saturation degree of mixes with various w/cm during moisture loss



(b) Water saturation degree of mixes containing pozzolan during water absorption

(d) Water saturation degree of mixes containing pozzolan during moisture loss

Fig. 8 Average water saturation degree (w^{ave}) of 7.5 cm cubic specimens during water absorption and moisture loss



(a) Water absorption tests

(b) Moisture loss tests

Fig. 9 Fitting of the experimental data to the numerical model for various concrete mixes (12.5 cm cubic specimens)

Table 5 The calculated moisture transfer coefficients during wetting and drying

Code	W40	W45	W50	W55	SF7.5	Z10
	12.5 cm cubic specimen					
$D_w^d \times 10^{-8}\ (m^2/s)$	3.8	3.6	3.4	3.0	6.0	3.9
β	2.8	2.1	1.5	1.1	3.5	2.6
R-Square	0.99	0.99	0.99	0.99	0.99	0.99
$D_d^s \times 10^{-10}\ (m^2/s)$	2.7	3.2	3.4	3.8	1.2	1.7
α	0.05	0.05	0.05	0.05	0.05	0.05
w_{cr}	0.8	0.8	0.8	0.8	0.8	0.8
N	6	6	6	6	4	5
R-Square	0.98	0.99	0.98	0.98	0.98	0.98
	7.5 cm cubic specimen					
$D_w^d \times 10^{-8}\ (m^2/s)$	3.9	3.5	3.3	3.1	6.2	3.9
β	2.8	2.0	1.5	1.1	3.7	2.5
R-Square	0.99	0.99	0.99	0.99	0.99	0.99
$D_d^s \times 10^{-10}\ (m^2/s)$	2.6	3.1	3.4	3.7	1.3	1.7
α	0.05	0.05	0.05	0.05	0.05	0.05
w_{cr}	0.8	0.8	0.8	0.8	0.8	0.8
N	6	6	6	6	4	5
R-Square	0.99	0.99	0.99	0.99	0.99	0.99

6.2 Model results

In order to determine the moisture transfer coefficient of concrete with the aid of the numerical model from the experimental data, D_w was defined as a function of w using Eqs. (7)-(8) during wetting and drying, respectively. Considering the governing differential equation and the assumptions described in Section 4, D_w^d, D_w^s, β, α, w_{cr} and N were calculated by the least-square method following the procedure shown in Fig. 3.

The numerical results obtained from the model are presented in Table 5, and the curves fitted to the experimental data are plotted in Fig. 9. To validate the accuracy of the proposed numerical technique, a comparison was made in Fig. 10 between the average water saturation degree (w^{ave}) obtained at 6 and 12 months during the drying process (see Tables 6-7) and those predicted by the numerical model. The data are located very close to the 45° line, which shows that there is a good correlation between the moisture contents of concrete obtained from the experimental results and those from the numerical model after 6 and 12 months of exposure.

The test results performed by Ishida *et al.* (2007) and Neithalath (2006) were also used to verify the proposed method. The water transfer parameters approximated by the proposed numerical method are shown in Fig. 11. The proposed model captured the trend of the experimental data very well. The R-square value of the fitted data for both Neithalath's (2006) and Ishida *et al.*'s (2007) cases was 0.99. Therefore, it can be inferred that there is a strong agreement between the model outputs using approximated D_w and the experimental moisture gain and loss results.

Table 6 Average water saturation degree (w^{ave}) of 12.5 cm cubic specimens after 6 and 12 months of exposure to environment and their comparison with model prediction

	W40	W45	W50	W55	SF7.5	Z10
	Exposure time of 6 months					
Test results, y_i	0.531	0.505	0.477	0.447	0.584	0.548
Numerical predictions, f_i	0.525	0.496	0.472	0.445	0.577	0.556
Error, $(y_i\text{-}f_i)/y_i \times 100$	1%	2%	1%	0%	1%	1%
	Exposure time of 12 months					
Test results, y_i	0.462	0.436	0.399	0.363	0.483	0.469
Numerical predictions, f_i	0.456	0.425	0.396	0.369	0.499	0.480
Error, $(y_i\text{-}f_i)/y_i \times 100$	1%	2%	1%	2%	3%	2%

Table 7 Average water saturation degree (w^{ave}) of 7.5 cm cubic specimens after 6 and 12 months of exposure to environment and their comparison with model prediction

	W40	W45	W50	W55	SF7.5	Z10
	Exposure time of 6 months					
Test results, y_i	0.429	0.395	0.360	0.339	0.445	0.444
Numerical predictions, f_i	0.433	0.401	0.368	0.344	0.459	0.449
Error, $(y_i\text{-}f_i)/y_i \times 100$	1%	2%	2%	1%	3%	1%
	Exposure time of 12 months					
Test results, y_i	0.374	0.349	0.331	0.310	0.381	0.375
Numerical predictions, f_i	0.382	0.356	0.323	0.301	0.393	0.386
Error, $(y_i\text{-}f_i)/y_i \times 100$	2%	2%	2%	3%	3%	3%

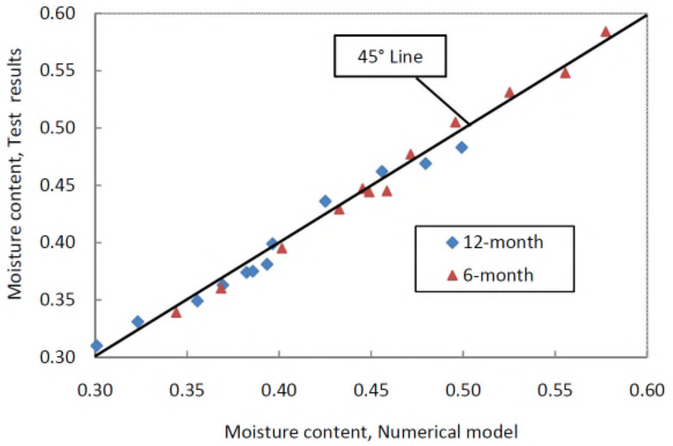
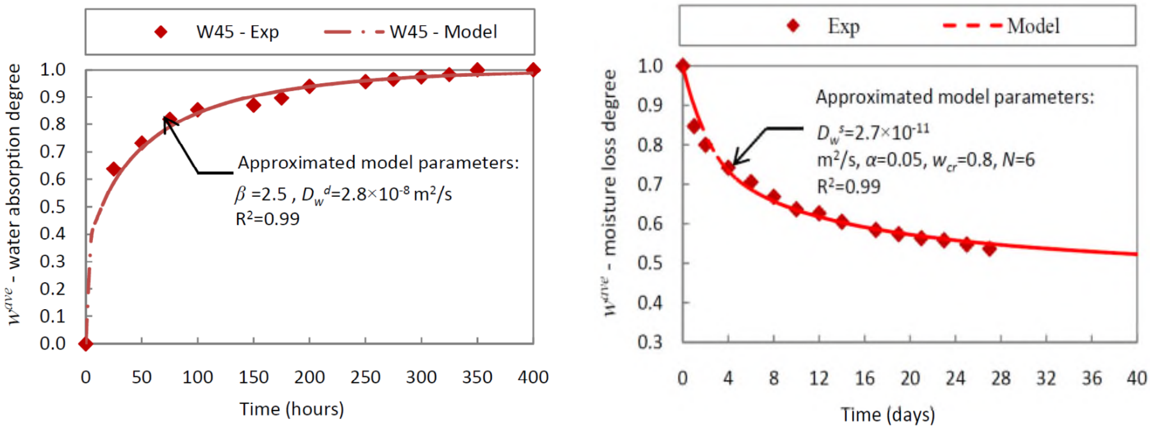


Fig. 10 Comparison between moisture contents of concrete obtained from the experimental results and those from the numerical model after 6 and 12 months of exposure

As can be seen in Table 5, β, D_w^d, and D_w^s vary with w/cm ratio and the use of pozzolanic materials; D_w^d increases as w/cm ratio decreases. Conciatori *et al.* (2011) reported that concrete



(a) Experimental results of tests performed by Neithalath (2006) on cement mortar with w/c=0.45 (1-D exposure of 50mm-thick specimen to water)

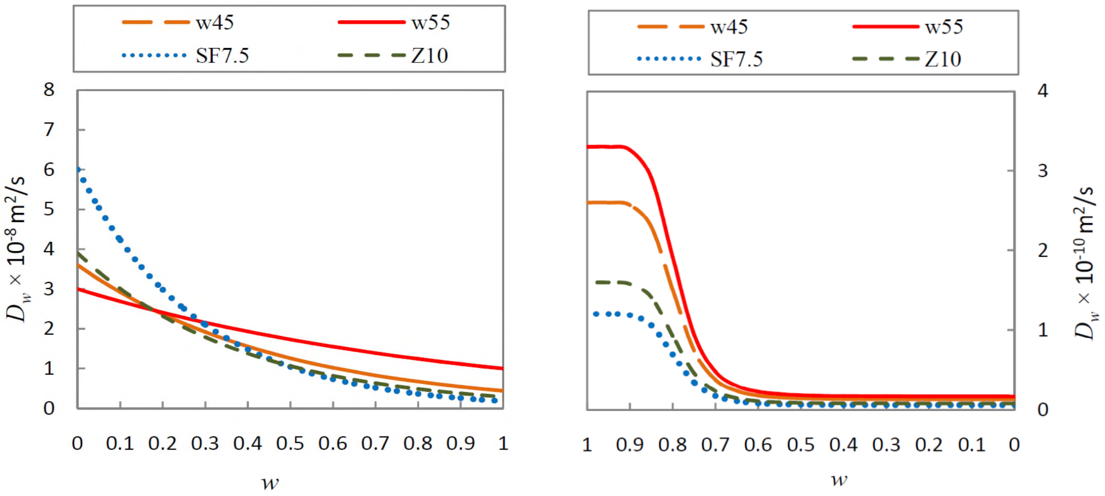
(b) Experimental results of tests performed by Ishida *et al.* (2007) on cement paste with w/c=0.50 (3-D exposure of 10 mm-cubic specimen to an environment with a 60% humidity)

Fig. 11 Comparison of the model outputs with other experimental data

with a lower w/cm ratio had a smaller pore size. Therefore, when partially saturated concrete is being wet, the water is quickly absorbed through capillary suction and consequently, by increasing the *w*, the moisture movement due to capillary suction, reduces (McCarter 1993). Indeed, D_w^d is indicative of initial capillary force which increases with lowering the pore diameter. Carlier *et al.* (2012) showed that, with a 30 percent decrease in w/cm ratio, capillary pressure increased by 20 percent. In this study, comparing W40 with W55 showed that D_w^d increased by 27 percent when w/cm ratio reduced by 27 percent. Therefore, the dependency of D_w^d to w/cm ratio corroborates that lowering the pore size by reducing the w/cm ratio causes higher capillary forces.

In addition, β decreases with increase in w/cm ratio because pore sizes in concrete with high w/cm ratio are larger than those in concrete with a lower w/cm ratio. Indeed, β indicates the degree of moisture dependency of D_w during water absorption. Replacement of cement by silica fume and zeolite led to a greater D_w^d and β due to the lower pore diameter as well as the lower porosity in the transition zone. D_w^d increased 67 percent and 8 percent when cement was partially replaced by silica fume and zeolite, respectively. The increase in D_w^d and β as the result of adding silica fume to concrete is consistent with the findings of Roy *et al.* (1995). They reported that silica fume concrete had a lower rate of absorption compared to the mixture without silica fume. Among other researchers, Morgan (1988) also found a lower absorption in silica fume concrete. Moreover, partial replacement of cement with silica fume and zeolite led to 59 percent and 34 percent reduction in the moisture transfer coefficient of saturated specimens during wetting.

As opposed to the wetting process, during the drying process, D_d^s increases with increase in w/cm ratio (Table 5) which is an indicator of the dominant role of surface tension and capillary wall action. Since surface tension holds water molecules against the solid surface, evaporation becomes more difficult as layers of water molecules are removed (Aquino *et al.* 2004). In other words, with an increase in w/cm ratio, the moisture trapped in capillary pores is released to the air easier. D_d^s reduced by 29 percent with 27 percent decrease in w/cm. Furthermore, silica fume and zeolite respectively result in 53 percent and 38 percent reduction of D_d^s during the drying process.



(a) During water absorption (wetting) (b) During moisture loss (drying)

Fig. 12 Moisture transfer coefficient versus pore water saturation degree (w) calculated by the model

In cement partially replaced with silica fume or zeolite, the diameter of the capillary pores decreases, leading to an increase in capillary surface tension for moisture impounding. This phenomenon would hinder the moisture release process from the concrete.

In Fig. 12, a parametric study was conducted using the results of the model to evaluate the effect of w on the water transfer coefficient of concrete in various mixture proportions. As demonstrated in Fig. 12, D_w strongly depends on w and decreases exponentially with an increase in the water content of concrete pores in the wetting state. D_w of the silica fume concrete decreased more than 30 times with increase in w from zero to 1.0. Previous test results by Parrot (1994) also indicated that the water absorption rate was very sensitive to the moisture content of the concrete. The lower the w is, the greater the total volume of pores are empty and available to be filled with water during the water absorption test. This was also observed by Conciatori *et al.* (2011) who reported that D_w decreased during the initial exposure to water.

7. Conclusion

In this paper, a practical method was introduced wherein the moisture transfer coefficient of concrete (D_w) was successfully approximated using a simple weight measurement of concrete specimens over time during water absorption and moisture loss. A comparison between the model predictions and long-term experimental results properly verified the acceptable performance of the method. The proposed method was also verified by the results of other researchers. Dependency of the moisture transfer coefficient (D_w) to the water saturation degree (w) of concrete pores was numerically demonstrated using an exponential function during wetting. D_w of the silica fume concrete decreased more than 30 times with increase in w from zero to 1.0. The moisture transfer coefficient (D_w) depends on w/cm of concrete; by lowering w/cm, D_w increased during the initial absorption; however, as time progressed, D_w significantly decreased with an increase in w. Partial replacement of cement with silica fume and zeolite led to a significant reduction in the saturated state of moisture transfer coefficient during wetting and drying. In comparison, silica fume was more effective than zeolite in reduction of D_w in concrete.

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