The Effect of Moisture Transport on Chloride Penetration in Concrete

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This paper presents results of an experimental investigation on the effect of moisture transport on chloride penetration in partially saturated concrete. The paper includes the development of an experimental setup, analysis of experimental data, and formulation of the governing equations to characterize the moisture-chloride interaction in non-saturated concrete. The experimental setup consisted of two sets of fully and partially saturated concrete specimens that were exposed to chloride solutions. Humidity sensors were embedded in the concrete specimens to measure the internal relative humidity and the variation of humidity profiles over time. The governing equation that describes the chloride transport in saturated concrete was modified to account for the chloride movement induced by the moisture transport. The comparison of the chloride profiles obtained from the partially and fully saturated concrete specimens confirmed the coupling effect between the moisture transport and chloride penetration in concrete. The measured chloride and humidity profiles were analyzed to determine the coupling parameter in the governing equation. The analysis of the experimental data indicated that the coupling term in the governing equation is concentration dependent which means that the governing equation is nonlinear.

Keywords: chloride; moisture; transport process; partially saturated concrete; durability.

INTRODUCTION

Reinforced concrete structures such as bridge decks, parking garage floors and marine structures that are located in splash and tidal zones are subject to a combined attack of moisture and chloride penetration. The interaction between the moisture and chloride penetration affects the durability of the reinforced concrete structures. The corrosion of the reinforcement in concrete takes place when the chloride content in contact with the steel surface has reached a threshold value and the moisture content in the concrete is sufficiently high. Therefore, the interaction between chloride ions and moisture in concrete is very important for long-term performance of reinforced concrete structures.

There are two different cases for the transport of chloride and moisture in concrete: fully saturated and partially saturated. In fully saturated concrete, the pores inside the concrete are completely filled with moisture, and the dominant mechanism for both chloride and moisture transport is the concentration gradient of chloride. In other words, the chloride concentration gradient not only drives the chloride penetration but also results in moisture movement in the concrete. In the second situation, where the concrete is partially saturated, both the moisture concentration and the chloride concentration gradients result in the moisture transport as well as the chloride penetration. In this case, both concentration gradients are driving forces for the transport processes.

Hong and Hooton (1999) examined the effect of drying and wetting cycles on the chloride ingress in high performance concrete. Their test results indicated that longer drying periods results in higher rates of chloride penetration. Field experience with concrete structures in marine environment shows that the part of the structures that are exposed to subsequent drying and wetting cycles in the tidal zone are more susceptible to corrosion damage when compared

with other parts in the submerged and atmospheric zones. A test results on a 22 year old marine structure demonstrated that the degree of moisture saturation has a great influence on the chloride diffusion in concrete (Guimaraes et al. 2000 and 2004). Nilsson (2000) presented a model for chloride ingress in concrete exposed to seawater splash or de-icing salt. In the model, the chloride diffusion and convection are described as functions of the concrete moisture content. Tong and Gjorv (2001) investigated the chloride diffusivities from steady-state and non-steady state migration test. The comparison showed that the chloride diffusivity for the non-steady state condition is about 10 times higher than that the steady-state case. Miller et al. (2004) evaluated the chloride ingress in concrete exposed to drying and wetting cycles and submerged concrete. Their test results showed that those different environmental conditions result in different chloride ingress rates. For the concrete exposed to drying and wetting cycles, chlorides penetrate into the concrete due to both sorption and diffusion, while the diffusion is the only transport mechanism for submerged concrete. de Vera et al. (2007) proposed a test method for predicting the chloride diffusion coefficients through partially saturated concrete. Their test results revealed that lowering the relative humidity inside concrete decreases the chloride diffusion coefficient. Nielsen and Geiker (2003) derived a model for the chloride diffusion in partially saturated cementitious material. In their model, the chloride diffusion coefficient depends on the degree of saturation.

Ababneh and Xi (2002) conducted a systematic experimental study on the effect of chloride penetration on the moisture transport. Their test results showed that even if the concrete is saturated and there is no moisture gradient, the moisture transport is made possible by the chloride gradient, which is similar to what happened in the moisture transport process in soil driven by chemical gradients (Lu and Likos 2004). Specifically, they found that (1) the coupling

72 effect of chloride penetration on the moisture transport is significant and it should be considered
73 in the governing equation for moisture transport in concrete; (2) the coupling effect can be
74 characterized by an additional term in the governing equation g for moisture transport, and (3)
75 the addition term is proportional to the chloride gradient and the proportional parameter (the
76 coupling parameter for the effect of chloride penetration on moisture transfer) can be determined
77 experimentally.

78 The present study is a continuation of the study conducted by Ababneh and Xi (2002),
79 but focusing on the coupling effect of moisture transfer on chloride penetration. In the present
80 study, we established an experimental method to study the coupling effect and we developed a
81 theoretical approach to determine the coupling parameter using the test data. In the following
82 sections, theoretical formulations related to the two transport processes of moisture and chloride
83 were described first. Additional terms representing the coupling effects were added into the
84 conventional governing equations. Then, a special experimental setup was developed, which
85 was used to study the coupling effect. Test data were obtained by using the special experimental
86 setup, and the test data were analyzed to determine the coupling parameter for the effect of
87 moisture transfer on chloride penetration.

88 89 **RESEARCH SIGNIFICANCE**

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91 In real-life situations, concrete structures are not used under the condition of fully or
92 permanently saturated; therefore the chloride penetration process driven by the chloride
93 concentration gradient is not the only mechanism for the chloride penetration in concrete. The
94 aim of this research is to quantify how the moisture transport in non-saturated concrete affects
95 the chloride penetration process. Once the role of moisture transport is quantitatively

characterized, the penetration of chloride into non-saturated concrete structures can be accurately modeled and predicted. Chloride concentration profiles are usually used to estimate the time for the chloride concentration to reach the corrosion threshold for reinforcing steel bars. A more realistic prediction of the chloride concentration profiles in concrete will help the design and construction of durable reinforced concrete structures.

BASIC FORMULATION

Usually, the transport of moisture and chloride in concrete can be described by conventional Fick's first law: the flux of moisture, J_H , is proportional to the moisture gradient or the gradient of pore relative humidity in concrete, H ; and the flux of chloride, J_{Cl} , is proportional to the concentration gradient of free chloride ions C_f

$$J_H = -D_{H-H} \text{grad}(H) \quad (1)$$

$$J_{Cl} = -D_{Cl-Cl} \text{grad}(C_f) \quad (2)$$

In Eqs. (1) and (2), there are two material parameters. D_{H-H} is the humidity diffusion coefficient, and D_{Cl-Cl} the chloride diffusion coefficient. Using mass conservation equation and Eqs. (1) and (2), two partial differential equations can be obtained (the so-called Fick's second law):

$$\frac{\partial w}{\partial t} = -\text{div}(J_H) = \text{div}[D_{H-H} \text{grad}(H)] \quad (3)$$

$$\frac{\partial C_t}{\partial t} = -\text{div}(J_{Cl}) = \text{div}[D_{Cl-Cl} \text{grad}(C_f)] \quad (4)$$

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120 in which w is the moisture content in concrete, and C_t the total chloride content in concrete
 121 including the bound chloride. By solving Eqs. (3) and (4), the two diffusion coefficients can be
 122 inversely determined if concentration profiles of moisture and chloride are available.

123 In this study, we focus on the coupled moisture and chloride transport processes, and we
 124 consider the chloride and moisture gradients as the two driving forces acting simultaneously in
 125 concrete. Therefore, the conventional Fick's first law must be modified (Ababneh and Xi 2002).
 126 We want to emphasize that the moisture content in concrete is not treated separately as liquid and
 127 vapor phases, and they are combined together and represented by the pore relative humidity, H ,
 128 as shown in Eqs. (1) and (3) (Bazant and Najjar 1972; Xi et al. 1994a; Xi et al. 1994b; Xi et al.
 129 2000). This treatment is valid for concrete mainly because concrete is a porous media with very
 130 fine pore structure, and the tortuosity of the pore structure is very high. As a result, the majority
 131 of moisture in concrete is in a state of multiple layer condensation of water molecular attached to
 132 the wall of pores, except in a few large capillary pores where pure liquid phase exists (Xi et al.
 133 1994a). The pore structure and moisture state of concrete are significantly different from
 134 conventional porous media in which the majority of moisture is in the liquid phase, and fluid
 135 flow takes place under liquid pressure. Considering the special situation for concrete, the
 136 advection effect usually represented by fluid velocity for conventional porous media can be
 137 replaced by the moisture gradient. Thus, in this study, the flux of chloride ions is composed of a
 138 flux due to free chloride concentration gradient and the flux due to moisture concentration
 139 gradient; and similarly the flux of moisture in concrete is assumed to consist of the flux due to

the gradient of moisture concentration as well as the flux due to the gradient of free chloride.

Eqs. (1) and (2) are thus modified and become

$$J_H = -D_{H-H} \text{grad}(H) - D_{H-Cl} \text{grad}(C_f) \quad (5)$$

$$J_{Cl} = -D_{Cl-Cl} \text{grad}(C_f) - D_{Cl-H} \text{grad}(H) \quad (6)$$

In Eqs. (5) and (6), there are four material parameters. D_{H-H} and D_{Cl-Cl} have the same meanings as in Eqs. (1) and (2); D_{H-Cl} is the coupling parameter for the effect of chloride penetration on moisture transport, and D_{Cl-H} the coupling parameter for the effect of moisture transport on chloride penetration.

Using Eqs. (5) and (6) and considering mass conservation, two partial differential equations can be obtained (may be called the modified Fick's second law):

$$\frac{\partial C_f}{\partial t} = -\text{div}(J_{Cl}) = \text{div}[D_{Cl-Cl} \text{grad}(C_f)] + \text{div}[D_{Cl-H} \text{grad}(H)] \quad (7)$$

$$\frac{\partial w}{\partial t} = -\text{div}(J_H) = \text{div}[D_{H-H} \text{grad}(H)] + \text{div}[D_{H-Cl} \text{grad}(C_f)] \quad (8)$$

The first terms on the right hand side of Eqs. (7) and (8) represent the direct effects of the two driving forces (chloride concentration gradient and moisture concentration gradient) on the two transport processes, respectively; and the second terms reflect the coupling effects. As a result, Eqs. (7) and (8) are fully coupled partial differential equations. In order to solve the two

coupled equations, the two coupling parameters must be determined first. To this end, Ababneh and Xi (2002) designed a test to determine the coupling parameter D_{H-Cl} in Eq. (8), which represents the effect of chloride penetration on moisture transport. Their test data showed that the coupling term is very significant and the coupling parameter D_{H-Cl} is not a constant but depends linearly on chloride concentration. The experimental study described in the following sections of this paper is aimed at determining the other coupling parameter D_{Cl-H} in Eq. (7), representing the effect of moisture transport on chloride penetration.

It is important to point that the two coupling parameters, D_{H-Cl} and D_{Cl-H} are not interrelated like in the case of conventional porous media, and thus one of them cannot be determined based on the other one. In general, Bazant and Thonguthai (1978, 1979) pointed out that the coupling parameters for concrete (such as the coupling between moisture and temperature) cannot be derived theoretically based on the reciprocal theory of irreversible thermo-dynamics.

It is also important to point out that chloride ions move around in the concrete together with other ions such as calcium ions and hydroxyl ions, and the flux equations, Eqs. (5) and (6) could be more complex when the multi-species transport phenomena is considered (Damrongwiriyanupap et al. 2013; Damrongwiriyanupap et al. 2014). In this study, we focused on the coupling effects between moisture and chloride and the other ionic coupling effects were not considered.

EXPERIMENTAL STUDY

The basic idea of the experimental study is shown in Fig. 1 and 2, which is a ponding test with two different experimental setups. The first setup is shown in Fig. 1, in which the concrete

specimen is partially saturated and exposed to a NaCl solution on the top surface. Since the concrete is not fully saturated (the internal humidity in concrete is lower than 100%), there are two driving forces in the specimen for the moisture and chloride transport, they are moisture and chloride concentration gradients. The second setup is shown in Fig. 2, in which the concrete specimen is fully saturated and exposed to the same NaCl solution on the top surface as in the first setup. On the bottom surface, the specimen is exposed to water. Since the concrete is fully saturated all the time, there is only one driving force in the specimen for the chloride transport: the chloride concentration gradient (neglecting gravity force). After a certain ponding period, the chloride concentration profiles in the two concrete specimens are measured and compared. If the profile in the initially partially saturated specimen (Fig. 1) is higher than that in the fully saturated specimen (Fig. 2), the difference must be due to the moisture gradient in the partially saturated specimen. The difference in the chloride concentration can be used to determine the coupling effect.

The same ponding test setup can be used for concrete specimens exposed to chloride solutions of different concentrations (3% and 5% were used in this study). The concentration profiles will be compared. If there is any difference in the profiles, it means that the coupling effect is concentration dependent.

The concrete samples were designed as four inch diameter cylinders with heights of two inches and three inches, respectively. The samples used for the non-saturated concrete were embedded with SHT75 Sensirion humidity and temperature sensors. These sensors were used to measure humidity profiles in the concrete, which provide necessary information for determining the coupling parameter D_{Cl-H} . The sensors were embedded in small voids in concrete and wrapped with GorTex fabric. The fabric allows water vapor to pass and blocks the liquid water.

It was used to protect the sensors so there is no direct contact of the sensors with salt solution, and it also provides a breathable interface so that the humidity readings would be accurate. Two sensors were placed in each sample as shown in Fig. 1, the first sensor was placed 1 in. [25 mm] off center and 1 in. [25 mm] from the top surface; and the second sensor was placed at the center of the sample, 2 in. [50 mm] from the top surface. The samples were cast, de-molded after 24 hours and stored in the moist room for 28 days.

The mixture proportions of the concrete used in this study were shown in Table 1. The coarse aggregate was crushed limestone, the fine aggregate was river sand, and the cement was Type I Portland cement. After 28 days curing, the 2 in. [50 mm] depth samples were immersed in water for 30 days to achieve full saturation and the 3 in. [75 mm] samples were exposed to air in the laboratory environment (temperature = 22.8°C [73°F] and relative humidity = 32%) for 30 days to achieve partial saturation. The compression test was performed on concrete cylinders with dimensions of 4x8 in. [100x200 mm] made of the same mix. The average compressive strength of the concrete was 3.32 ksi [22.87 MPa].

The concrete samples were then put into their respective experimental set-ups: exposed to sodium chloride solution with the concentration of 3% NaCl (by weight), or 5% NaCl, or exposed to distilled water. The chloride solutions were ponded on top of the samples and had a depth of 2 in. [50 mm]. The distilled water was ponded from the bottom face. The concrete samples exposed to the NaCl solutions were removed from the solutions after certain exposure periods, and allowed to dry for one day at room temperature. Samples of concrete powder were collected at three different locations, at 0.25 in. [6.25 mm] depth increments from the surface exposed to the NaCl solution. The electro-chemical analysis of the powder samples was completed using the Rapid Chloride Test (RCT) method. This analysis resulted in a profile of

total chloride concentration as weight percentage of concrete weight. The RCT test kit was manufactured by *Germann Instruments, Inc.*

EXPERIMENTAL RESULTS

The result of humidity measurements are shown in Fig. 3 through Fig. 6. The figures display the variation of relative humidity with time along the axis of the cylindrical concrete specimen. Figs. 3 and 4 present the humidity profiles at a depth of 1 in. [25 mm] from the top of the surface exposed to 3 and 5% NaCl solution, respectively. While Figs. 5 and 6 show the profiles at depth of 2 in. [50 mm]. As shown by the figures, the average initial relative humidity readings of the partially saturated concrete samples were 69.5% in the center and 71.2% one inch [25 mm] off center. These are the average values found from all the sensor readings at the initial stage. By evaluating the humidity data, we found that all humidity sensors' reading reached saturation in about one month period for the samples exposed to chloride solutions.

The total chloride concentration profiles obtained from the tests in the present study after 30 and 60 days of exposure to NaCl solutions are shown in Fig. 7 through 10. Figs. 7 and 8 present the profiles obtained from the specimens exposed to 3% NaCl solution, while Figs. 9 and 10 show the results from the samples exposed to 5% NaCl solution. All chloride concentration profiles show that chloride concentrations are higher in the initially partially saturated concrete than the fully saturated concrete, at the same depths. In a preliminary study (Ababneh 2002), a similar result was obtained. All of the test data indicated that there is a significant coupling effect between the two transport processes. Therefore, in Eq. (6), the second term on the right

hand side representing the coupling effect on the flux of chloride cannot be neglected. The two governing equations for the moisture and chloride transports, Eqs. (7) and (8), are fully coupled, and are not two independent equations as shown in Eqs. (3) and (4).

EVALUATION OF THE COUPLING PARAMETER D_{Cl-H}

The theoretical approach

Eqs. (7) and (8) can be used to evaluate the two coupling parameters and the two diffusion parameters based on the experimental results. In the present study the focus is to use Eq. (7) to evaluate the coupling parameter D_{Cl-H} . First, we rewrite Eq. (7) as Eq. (9)

$$\left(\frac{\partial C_t}{\partial t} \right)^t = \left(\frac{\partial C_t}{\partial t} \right)^{C_f} + \left(\frac{\partial C_t}{\partial t} \right)^H \quad (9)$$

in which the left hand side represents the variation of total chloride content with the combined effect of two driving forces: free chloride C_f and internal moisture H . The first and the second term on the right hand side represent the variation of total chloride concentration due to the chloride transport and the moisture transport, respectively. We can express the second term on the right hand side of Eq. (9) as:

$$\left(\frac{\partial C_t}{\partial t} \right)^H = \text{div}(J_{Cl-H}) \quad (10)$$

in which the divergence can be calculated as

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$$276 \quad \text{div}(J_{Cl-H}) = \frac{A}{V} J_{Cl-H} = \frac{A}{A\Delta x} J_{Cl-H} = \frac{J_{Cl-H}}{\Delta x} \quad (11)$$

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278 in which V is the volume of concrete between two adjacent points, $V = A\Delta x$, where A is the
 279 surface area and Δx is the distance between two adjacent points on a concentration profile. In
 280 Eq. (11), the flux J_{Cl-H} due to the coupling effect can be expressed as

281

$$282 \quad J_{Cl-H} = D_{Cl-H} \text{grad}(H) = D_{Cl-H} \frac{\Delta H}{\Delta x} \quad (12)$$

283 Substituting Eq. (12) into Eq. (11), and then into Eq. (10) and Eq. (9) yields

284

$$285 \quad \left(\frac{\partial C_t}{\partial t} \right)^t = \left(\frac{\partial C_t}{\partial t} \right)^{c_f} + D_{Cl-H} \frac{\Delta H}{(\Delta x)^2} \quad (13)$$

286

287 Solving D_{Cl-H} from Eq. (13)

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$$289 \quad D_{Cl-H} = \left[\left(\frac{\partial C_t}{\partial t} \right)^t - \left(\frac{\partial C_t}{\partial t} \right)^{c_f} \right] \frac{(\Delta x)^2}{\Delta H} \quad (14)$$

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291 in where the terms and parameters on the right hand side need to be evaluated from the test data
 292 of both initially partially saturated specimens and initially fully saturated specimens:

$\left(\frac{dC_t}{dt}\right)^i$ = rate of total chloride variation from initially partially saturated condition

293 $\left(\frac{dC_t}{dt}\right)^{C_f}$ = rate of total chloride variation from initially fully saturated condition

Δx = distance between two chloride concentration readings

ΔH = humidity readings at two different locations at the same time

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295 **Determination of the coupling parameter D_{Cl-H} using experimental results**

296 In Eq. (14), several quantities need to be determined based on the experimental results,
297 such as the humidity gradient $\Delta H / \Delta x$, and rates of total chloride variation from both partially
298 saturated and fully saturated samples, $(\partial C_t / \partial t)^i$ and $(\partial C_t / \partial t)^{C_f}$. All these quantities can be
299 evaluated based on the test data obtained from cylinder specimens as shown in Fig. 7 to Fig. 10.

300 The samples had reached saturation at 30 days, so to include the entire process the
301 average of the initial relative humidity readings at 0 days and the relative humidity readings at 30
302 days was used. Using the average readings and assuming that at the bottom surface of the
303 samples the relative humidity was equal to the relative humidity of the laboratory environment
304 (Fig. 1 for initially partially saturated specimens), the internal relative humidity distribution
305 along depth of the samples, were plotted and shown in Figs. 11 and 12 as solid dots. The
306 humidity distributions were then estimated by using the equations from fitting of the test data as
307 shown in Figs. 11 and 12 as solid lines. These equations were used to find ΔH in the region of
308 the concrete where the pore relative humidity (RH) is below 95%. For the surface region with
309 very high RH ($100\% > RH > 95\%$), a linear distribution of RH was assumed.

310 The calculation of $(\partial C_t / \partial t)^i$ and $(\partial C_t / \partial t)^{C_f}$ was completed using the chloride
311 concentrations measured from the initial partially saturated and fully saturated concrete samples

at 30 days, respectively. The initial chloride concentrations were assumed to be zero at all locations. Once ΔH , $(\partial C_t / \partial t)^f$, and $(\partial C_t / \partial t)^{C_f}$ are calculated, D_{Cl-H} can be evaluated using Eq. (14). Δx is equal to 0.25 in. [6.25 mm], which is the distance between the depths where concrete powder samples were collected. Fig. 13 displays the plots of D_{Cl-H} versus chloride concentration for exposure to 3% NaCl solution and 5% NaCl solution, respectively.

As one can see from Fig. 13, D_{Cl-H} increases monotonically with chloride concentration and therefore, D_{Cl-H} is concentration dependent. For the chloride concentration level up to 0.25% by concrete weight, D_{Cl-H} may be considered as a linear function of the concentration. A simplified model for the coupling parameter D_{Cl-H} can be derived from the figure for the concentration up to 0.25%:

$$D_{Cl-H} = 2C_t \quad (15)$$

in which C_t is in %, and D_{Cl-H} is in kg/(m-sec). The proportional constant (the value 2) in Eq. (15) depends on concrete mix design parameters. In another word, for a concrete with a mix design different from the one used in the present study, the proportional constant, i.e. the initial slope of the curve in Fig. 13, will be different. More systematic studies will need to be conducted to determine the effect of concrete mix design on the coupling parameter.

Another important observation from Fig. 13 is that D_{Cl-H} decreases to zero when the free chloride concentration is small. This is an important conclusion. Considering the case of moisture transport for Eq. (6), where $C_f = 0$ and no chloride on the boundary. In this case,

since there is no chloride in the system, both the gradient of free chloride and chloride flux must be zero, i.e. $grad(C_f) = 0$ and $J_{Cl} = 0$. On the other hand, since $grad(C_f) = 0$, Eq. (6) becomes

$$J_{Cl} = -D_{Cl-H} grad(H) \quad (16)$$

For the case of moisture diffusion, $grad(H) \neq 0$, and therefore, D_{Cl-H} must be zero when $C_f = 0$ in order to have $J_{Cl} = 0$. Basically, the two requirements for D_{Cl-H} are that D_{Cl-H} must be concentration dependent and D_{Cl-H} must be zero when $C_f = 0$. The present test data showed that both basic requirements are met.

Another important conclusion that can be obtained from the concentration dependence of D_{Cl-H} is that Eq. (7) is not a linear equation. For a linear diffusion equation, the coupling parameter as well as the diffusivities are constants. As shown in our experimental results, the coupling parameter, D_{Cl-H} , is a function of chloride concentration, see Fig. 13. Ababneh and Xi (2002) already showed that the other coupling parameter D_{H-Cl} in Eq. (5) is also concentration dependence. Therefore, when the two coupling parameters are inserted into Eq. (7) and Eq. (8), the two equations become not only fully coupled but also nonlinear.

CONCLUSIONS

1. The chloride penetration in non-saturated concrete is driven by two driven forces. One is related to the chloride concentration gradient, and the other to the moisture gradient. In this paper, a new experimental method was developed for studying the effect of moisture transport on chloride penetration in concrete. Chloride concentration profiles were measured in initially

partially saturated and initially fully saturated concrete samples, and the concentration profiles of were compared. The test data showed that the moisture transport significantly increases the chloride penetration process in concrete. So, there is a significant coupling effect of the moisture transport on chloride penetration.

2. To take into account the coupling effect, a coupling term was added to the chloride flux equation, the Fick's first law for chloride transport in concrete. The coupling term in the chloride flux equation is expressed as a function of the moisture gradient, and D_{Cl-H} is the coupling parameter for the moisture gradient. Therefore, the chloride penetration and moisture transport are interrelated with each other. They are two fully coupled transport processes in partially saturated concrete.

3. Using the modified chloride flux equation, an analytical method was developed to evaluate the coupling parameter D_{Cl-H} based on the experimental results obtained in the present study. The results showed that D_{Cl-H} is not a constant but increases with chloride concentration. Up to the total chloride concentration of 0.25% (weight of chloride/weight of concrete), D_{Cl-H} is a linear function of the total chloride concentration.

4. The concentration dependence of the coupling parameter D_{Cl-H} resulted in the nonlinearity of the governing equation for chloride penetration in non-saturated concrete.

5. Our previous study (Ababneh and Xi 2002) showed that the other coupling parameter D_{H-Cl} (the effect of chloride penetration on moisture transfer) depends also on chloride concentration. Therefore, the two governing equations for moisture and chloride transport in concrete are not only fully coupled but also nonlinear. This is a great challenge for developing computational methods to solve these coupled nonlinear equations.

6. It should be pointed out that the above conclusions are based on the test data of the present study with one concrete mix design and two boundary chloride concentrations of 3% and 5% of NaCl. More studies need to be conducted to investigate the effect of concrete mix design and higher chloride concentrations.

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Table 1 - Concrete mix proportions

Mix	Proportions
water-cement ratio (w/c)	0.55
aggregate volume fraction (g_v)	0.65
weight of water, lb/yd ³ [Kg/m^3]	394 [234]
weight of cement, lb/yd ³ [Kg/m^3]	641 [380]
weight of sand, lb/yd ³ [Kg/m^3]	1,184 [702]
weight of gravel, lb/yd ³ [Kg/m^3]	1,536 [911]

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Fig. 1 Initially partially saturated specimen, the top surface is exposed to NaCl solution with two humidity sensors in the specimen and the bottom surface is exposed to the laboratory environment. [1 in. $\approx$ 25 mm]

Fig. 2 Initially fully saturated specimen, the top surface is exposed to NaCl solution and the bottom surface is exposed to the water. [1 in. $\approx$ 25 mm]

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Fig. 3 - Variation of relative humidity with time at depth 1 in. [25 mm] from the top of the samples exposed to 3% NaCl solution.

Fig. 4 - Variation of relative humidity with time at depth 1 in. [25 mm] from the top of the samples exposed to 5% NaCl solution.

Fig. 5 - Variation of relative humidity with time at depth 2 in. [50 mm] from the top of the samples exposed to 3% NaCl solution.

Fig. 6 - Variation of relative humidity with time at depth 2 in. [50 mm] from the top of the samples exposed to 5% NaCl solution.

Fig. 7 - Chloride profiles for the specimens after 30 days of ponding with 3% NaCl solution. [1 in. $\approx$ 25 mm]

Fig. 8 - Chloride profiles for the specimens after 30 days of ponding with 5% NaCl solution. [1 in. $\approx$ 25 mm]

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Fig. 9 - Chloride profiles for the specimens after 60 days of ponding with 3% NaCl solution. [1 in. $\approx$ 25 mm]

Fig. 10 - Chloride profiles for the specimens after 60 days of ponding with 5% NaCl solution. [1 in. $\approx$ 25 mm]

Fig. 11 - Relative humidity vs. depth for specimens exposed to 3 % NaCl solution. [1 in. $\approx$ 25 mm]. Solid dots are test data and the solid line is an estimation based on the test data.

Fig. 12 - Relative humidity vs. depth for specimens exposed to 5 % NaCl solution. [1 in. $\approx$ 25 mm]. Solid dots are test data and the solid line is an estimation based on the test data.

Fig. 13 - Plot of chloride concentration for partially saturated at 30 days vs. $D_{Cl-H} \cdot [1 \text{ Kg/(m-sec)} \approx 0.056 \text{ lb/(in-sec)}]$