EFFECT OF CRACK WIDTH AND CHLORIDE BINDING ON CHLORIDE DIFFUSIVITY IN CRACKED RC BEAMS

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Abstract: This paper presents experimental and numerical results to study the effect of chloride binding and the crack width on the chloride transport in reinforced concrete beams subjected to flexure load. Reinforced concrete beams loaded in flexure to generate cracks were exposed to 8% of NaCl solution for three months. A crack influence function (F_w) was developed to correlate the crack width (w) and the ratio of chloride diffusion coefficient in the crack D_{cr} to the chloride diffusion coefficient in sound concrete D_e. Results of numerical simulation using COMSOL was seen to be in good agreement with the experimental results and thee mechanical behavior as well as the transport of the chloride in damaged RC beams was well predicted.

1 INTRODUCTION

Chloride-induced corrosion is one of the major causes of corrosion of reinforcement in concrete. In the Arabian Gulf region, the hot and arid environment has resulted in premature deterioration of concrete structures, requiring extensive repairs. The diffusion of the chloride ion in concrete plays an important role in limiting the service life of concrete structures. The main parameters affecting the chloride diffusivity of undamaged concrete including mix parameters, moisture contents and environmental conditions in concrete have been investigated in many researches (Tang and Nilsson [1], Saeeta et al. [2], Mangat and Mooloy [3]). Chloride diffusion is also significantly affected by physical adsorption/chemical reaction between the chloride ions and solid skeleton in the concrete. Modeling of chloride diffusion in saturated and partially saturated concrete, using finite element/finite difference method and Fick's law has been adopted in several researches to predict chloride diffusion coefficient. Various factors affecting the chloride ingress in concrete including the effect of chloride binding has been modeled (Xi and Bazant [4], Saetta et al. [2], Nielsen and Geiker [5]).

The structural members in service are in fact subjected to axial and flexural loads which results in development of microcracks and hairline cracks in the tension zone. In unstressed concrete, the chloride transport property is related to the porosity of concrete, while in cracked concrete, it is related in addition to porosity, to the microcracks and cracks. The prediction of service life of concrete beams stressed in compression and tension based on the data for unstressed concrete element could lead to erroneous predictions. Chloride diffusion in stressed concrete elements could be several orders in magnitude higher than the unstressed concrete. The rate of penetration of chloride is strongly influenced by the extent of stress-induced damage. This is analogous to the fact that permeability of damaged concrete is increased by several orders in magnitude.

Several investigations have been conducted to experimentally investigate the effect of cracking on chloride diffusion in concrete. Effect of cracks on concrete permeability and chloride penetration in concrete, by generating artificial crack in the concrete specimen, has been investigated extensively (Aldea et al. [6] Garces-Rodriguez and Hooton [7], Ismail et al. [8]). The diffusion coefficient increases with the increasing crack width for crack widths up to ~ 80 μm, beyond which cracks provides free concrete surface promoting 2-D chloride diffusion in the specimen.

Experimental studies on concrete elements in which micro and macro cracks were generated by the application of external compressive and flexural loads have been Samaha and Hover [9], Lim et al. [10], Gerard and Marchand [11] and Gowripalan et al. [12]. Gerard and Marchand reported an increase in concrete diffusivity by a factor ranging from 2 to 10 due to cracks in the concrete. Sahmaran [13] found that in flexurally loaded reinforced mortar specimen an increase in crack width resulted in an increase in the effective diffusion coefficient For cracks with widths less than 135 μm, the effect of crack widths on the effective diffusion coefficient of mortar was found to be marginal, whereas for crack widths higher than 135 μm the effective diffusion coefficient increased rapidly.

Pijaudier-Cabot et al. [14] stipulated that a strong interaction exists between material damage and transport properties of concrete. In concrete element with diffuse cracking, the material permeability is controlled by damage (decrease of average stiffness due to microcracking). In the case of localized microcracking, and after a macrocrack has formed, permeability is controlled by a power function of the crack opening (Poiseuille flow). A detailed observation on the penetration profile of chloride ions through and around a crack in reinforced concrete structures was carried by Win et al. [15]. Research parameters included water to cement ratio (w/c), single and multi-cracks, exposed direction, crack width, NaCl solution concentration and cover thickness. Ishida et al. [16] developed chloride transport model for sound and cracked concrete with crack widths up to 0.3 mm. The equilibrium relationship between free and bound chloride was modelled based on the experimental results for ordinary Portland cement, blast furnace slag, and fly ash and introduced into a thermodynamic coupled analytical system a non-linear binding model. The chloride transport was found to be very rapid along and cross the crack boundaries. Rahman et al [17] presented the effect of damage and cracking under compressive load on chloride migration in concrete.

This paper presents the numerical simulation of the coupled problem of chloride diffusion equation while accounting for chloride binding through concrete, as well as the crack width due to mechanical loading using a finite element idealization in a COMSOL Multiphysics environment [18].

2 CHLORIDE DIFFUSION IN SATURATED CONCRETE

Chloride transport in concrete based on the equation of mass balance in 1-D can be written as:

$$\frac{\partial C_t}{\partial t} + \frac{\partial J_c}{\partial x} = 0 \qquad (1)$$

Where C_t is the total chloride content (g of total chloride per g of concrete) $C_t = C_f + C_b$ and J_c is chloride flux (m/s). The total chloride content C_t can be expressed as the sum of the bound and free chloride, which can be expressed in term of the chloride isotherm or the chloride binding capacity $\partial C_b / \partial C_f$ as

$$\frac{\partial C_t}{\partial C_f} = 1 + \frac{\partial C_b}{\partial C_f} \qquad (2)$$

The diffusive flux of free chloride ions in saturated concrete and combining it with Eq. (1) and Eq. (2) the diffusion of free chloride in concrete can be written as reported by Tang and Nillson [1]:

$$\frac{\partial C_f}{\partial t} = F_b \frac{\partial}{\partial x}\left(D_e \frac{\partial C_f}{\partial x} \right) \qquad (3)$$

Where D_e is the intrinsic chloride diffusivity of concrete (m^2/s) and F_b is the chloride binding influence function and could be expressed from Eq. (2) as

$$F_b = \frac{1}{1 + \frac{\partial C_b}{\partial C_f}} \qquad (4)$$

3 EFFECT OF CRACK WIDTH ON CHLORIDE DIFFUSION

To consider the effect of the crack width on the diffusivity of chloride in concrete, a form of multivariate law for undamaged concrete is adopted in which the effective chloride diffusion coefficient in cracked concrete D_{cr} together with the impact of chloride binding is defined as:

$$D_{cr} = D_e \times F_b \times F_w \qquad (5)$$

Fb is the chloride binding influence function and F_w is the crack width influence function.

The 2-D form of diffusion equation of chloride ion for predicting time and spatial concentration of chloride in concrete considering the influence of crack width and chloride binding is given as follows:

$$\frac{\partial C_f}{\partial t} = D_{cr} \frac{\partial^2 C_f}{\partial x^2} + D_{cr} \frac{\partial^2 C_f}{\partial y^2} \qquad (6)$$

4 EXPERIMENTAL PROGRAM

To investigate the effect of crack width on chloride diffusion in concrete, reinforced concrete beams (150x150x1200 mm) were loaded in flexure using four points loading to the stipulated percentage levels of the ultimate flexural capacity of the beams. Four pairs of reinforced concrete beams were loaded up to 40%, 60%, 75% and 90% of the ultimate flexural capacity of beams and two beams serving as control were not subjected to any load. The surfaces of the beams were subsequently coated with epoxy, so that chloride penetration takes place only from tension and compression surfaces.

Two RC beams were loaded back to back in a steel frame and by tightening the nuts the stress-state prior to its unloading was achieved. The beams were kept immersed in 8% NaCl solution to simulate marine exposure condition for three months.

After this period, the specimens were cleaned and dried to remove the surface moisture and drilled at depths of 5, 15, 35, 50 and 75 mm at the different crack positions. The chloride profile was measured at about 500 mm from the edge of the beam and under the point load, the crack width range in this study was from 0.25 to 1 mm. In order to determine the water-soluble and the acid-soluble chloride concentration, three grams of the powder was obtained at each depth and tested according to AASHTO T-260. Free chloride content profile and a relationship between the crack width (w) and the ratio of chloride diffusion coefficient in the crack D_{cr} to the chloride diffusion coefficients in sound concrete D_e was established.

5 SIMULATION OF CHLORIDE DIFFUSION IN CRACKED CONCRETE

The 2-D structural mechanics using the Drucker-Prager yield criterion was first used to describe the ductile behavior of the RC beams where, the Drucker-Prager yield criterion can be written as:

$$f(I,\sqrt{J}) = \sqrt{J} + \alpha I = k \qquad (7)$$

in which $I = \sigma_{KK}$ is the hydrostatic component of the stress tensor, $J = \frac{1}{2}S_{ij}S_{ji}$ is the deviatoric stress tensor invariant, α and k are material constants which can be related to the friction angle ϕ and cohesion c of the Mohr-Coulomb criterion in several ways. For plane stress problem, the relation between the parameters is as follows:

$$\alpha = \frac{\sin\phi}{\sqrt{3}} \qquad k = \frac{2}{\sqrt{3}}\, c\cos\phi \qquad (8)$$

In this study, a value of c=4.8 MPa and friction angle ϕ =53^o was adopted, where these material parameters were found by calibration to match the experimentally determined P–Δ curve. The chloride transport problem was subsequently solved to advance the solution of the coupled problem of chloride diffusion and binding. Von Mises material model was used for the steel reinforcement in which E_s and F_{ys} was 190,000 MPa and 560 MPa, respectively. Fig. 1 shows the finite element model of the RC beam including dimensions and boundary conditions. The steel reinforcement was modeled as a plate represents the area of reinforcement in the beam with the same thickness of the concrete section.

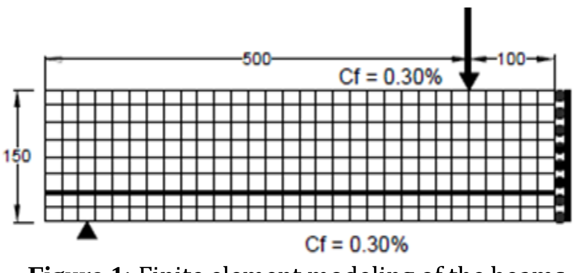

Figure 1: Finite element modeling of the beams.

Table 1 shows the parameters used in COMSOL model for simulation of mechanical load and chloride diffusion response. The coefficient of chloride diffusion parameter D_e was taken as 3.35×10^{-6} mm^2/s, the free chloride concentration C_f at the boundary was 0.30% per weight of concrete. Initial chloride content in the sample, C_i, was assumed to be zero.

Table 1: Parameters used in COMSOL model

Expression	Value
C_o	C_f =0.30% by wt. of conc.
f_{cr}	4 MPa
f_u	50 MPa
ε_{cr}	1.55e-4
ε_u	2.3e-3
E_c	29,000 MPa
E_s	190,000 MPa
F_{ys}	560 MPa
α	2.39
β	15.6
F_b	$1/(1+ \alpha/(1+\beta * C))$
F_w	120 for w<0.25 mm
	475w+1 for 0 <w<0.25
C_b	$\alpha C/(1+ \beta * C)$
C_t	C_b+C

6 RESULTS AND DISCUSSION

6.1 Mechanical behavior

The experimental and numerical results of load-deflection curve up to failure loading are shown in Fig. 2. The experimental results gives the cracking load of 7.5 kN and the ultimate load of 95 kN. These results match well with the cracking load calculated using ACI and COMSOL While both ACI and COMSOL show more stiffened behavior than the experimental results after the cracking load, the numerical simulation predict well the behavior of reinforced concrete beam when approaching to the ultimate load where the predicted ultimate load was 93 kN.

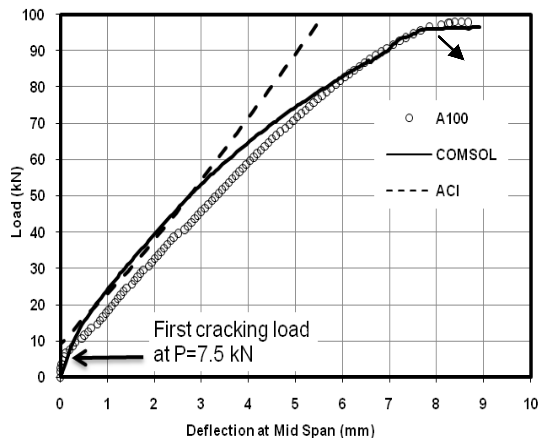

Figure 2: Experimental load-mid span deflection curve vs. ACI formula and COMSOL simulation.

6.2 Chloride binding isotherm

The results of free and bound chloride for different RC beams are presented in Fig. 3. The Langmuir binding isotherm was found to give the best fit to the data with a value 2.39 for α and 15.6 for β. The binding influence function F_b can be written as follows:

$$F_b = \frac{1}{\left(1 + \frac{2.39}{(1+15.6C_f)^2}\right)} \tag{9}$$

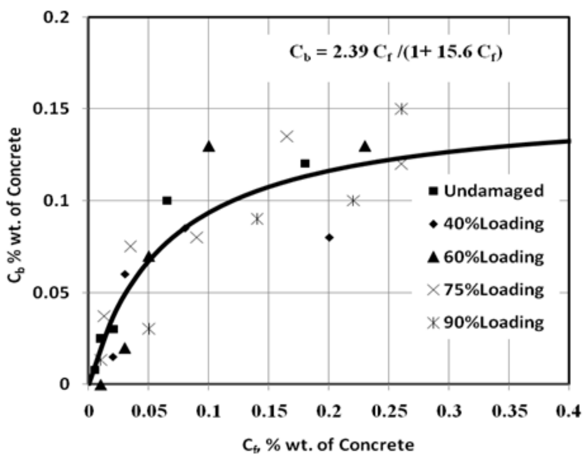

Figure 3: Relationship between free and bound chloride.

6.3 Effect of crack widths on chloride diffusivity

Fig. 4 shows the free chloride profile along the crack wall with different crack widths ranges from 0.25 to 1 mm in damaged RC beams. From Fig. 4, it could be noted although there is increase in the chloride content with increasing crack width, the effect of the crack width reduced with increase of depth of the crack.

Table 2 shows the correlation between crack width and chloride diffusion coefficients at various crack widths. The chloride diffusion coefficient in cracks tends to increase up to 125 times the chloride diffusion coefficients of sound concrete with crack widths of 1 mm.

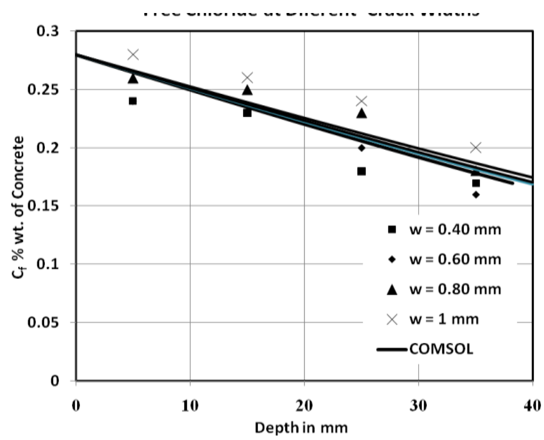

Figure 4: Free chloride profile a long crack walls with different crack widths.

Table 2: Correlation between crack function F_w and chloride diffusivity at various crack widths

Crack width in mm	D_{cr} (mm^2/s) $x\ 10^{-6}$	$F_w = D_{cr}/D_e$
Undamaged	3.35	1.0
0.25	350	104
0.4	378	113
0.6	389	116
0.8	385	115
1	423	125

The crack influencing function F_w, which gives the relationship between the crack width (w) and the ratio of chloride diffusion coefficient in the crack D_{cr} to the chloride diffusion coefficients in sound concrete D_e was established as follows:

$F_w = 120$ for $w > 0.25$

$F_w = 476w + 1$ for $0 < w > 0.25$ (10)

Kato et al. [19] also reported that the chloride content in cracked zone in concrete increase with the increase in the crack width up to 0.075 mm.

7 2-D COMSOL SIMULATION OF CHLORIDE DIFFUSION IN CRACKED CONCRETE

Two-dimensional numerical simulation of chloride diffusion in cracked beam was conducted using COMSOL software. Figure 7 shows the 2D free chloride distribution in the undamaged RC beams, at first cracking load, 10 kN, 40 kN, 65 kN and 90 kN flexural loading. The chloride diffusion at the cracks is higher as compared to uncracked portion under stress. The crack width influencing function was used control the transport of the chloride along the crack depth. To compare the experimental and the numerical results along the crack depth a one dimensional chloride profile was plotted in Fig. 4 at the position of maximum crack width about 500 mm from edge of the RC beam. From Fig. 4, it can be noted that the finite element simulation match well with the experimental results.

8 CONCLUSIONS

Experimental and numerical study of chloride penetration along the cracks in in RC beams damaged under flexural loads and exposed to 8% NaCl solution for three months was conducted. Langmuir chloride binding hypothesis coupled with chloride diffusion was used to assess chloride diffusion in cracked RC beams.

A crack influencing function F_w, was established to correlate the crack width (w) and the ratio of chloride diffusion coefficient in the crack D_{cr} to the chloride diffusion coefficients in sound concrete D_e. Using the approach outlined in this paper, the impact of cracking and chloride binding on chloride transport may be used for predicting the reduced service life of reinforced concrete structures subjected mainly to flexural stress fields.

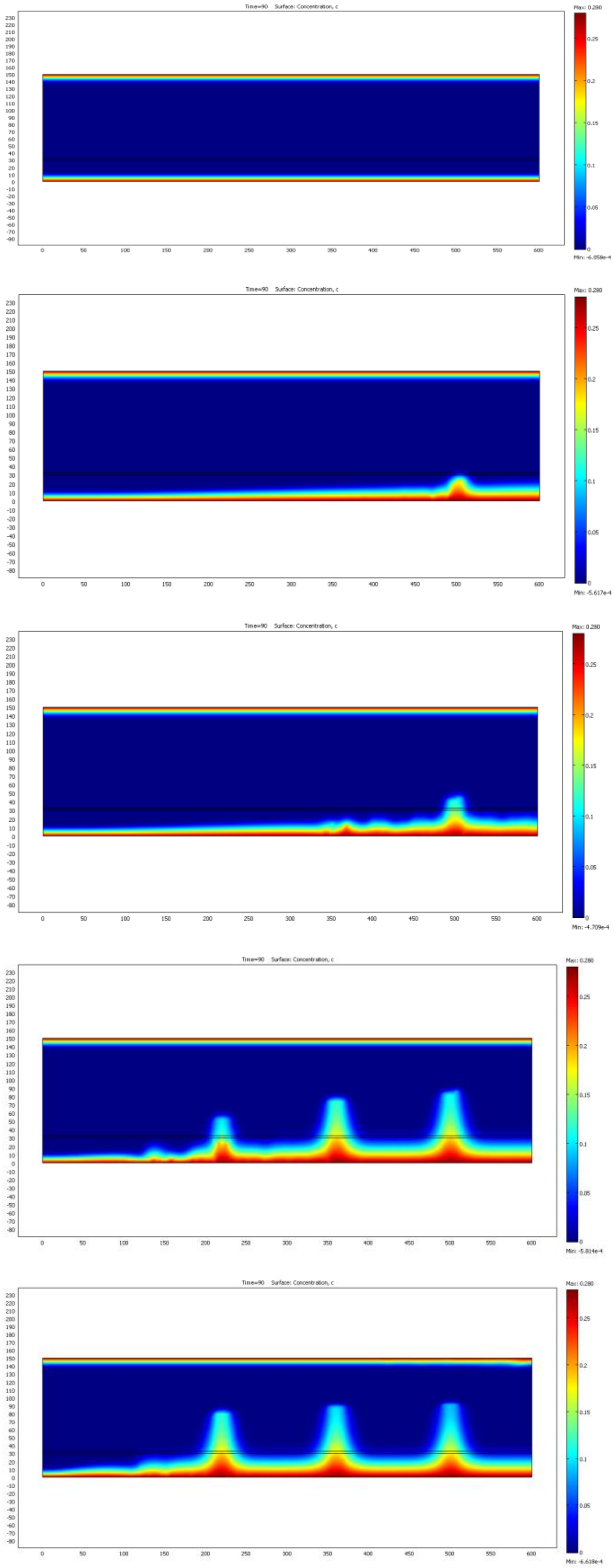

Figure 7: Free chloride distribution for undamaged, at first cracking, 40,75 and 90 kN loading.

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