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EFFECTS OF CRACKING ON THE TRANSPORT CHARACTERISTICS OF REINFORCED CONCRETE

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ABSTRACT

Concrete has been used as the construction material of choice in harsh environments due to its good durability relative low cost. Reinforced concrete structures, on the other hand, exhibit some vulnerability under saline environments due to reinforcement corrosion. The penetration of chloride ions plays a crucial role in rebar corrosion and, hence, for the durability and service life of a structure. The problem is even more acute once cracking occurs. Comprehension and correct modeling of transport of moisture and chemicals in damaged concrete under severe environmental conditions are the object of the present study. Chloride ions' ingress in both the pre-cracked and cracked regimes has been addressed. The effect of a single crack allowed to interact with the surrounding matrix on the chloride ingress is investigated. The presence of cracks is shown to have a dramatic impact on chloride penetration. Moisture movement and chlorides ingress both, in the matrix and through the crack, are tested and modeled according to the models presented in this paper.

Keywords: Cracking, Concrete, Corrosion, Transport Properties, Moisture Flow, Porous Media.

INTRODUCTION

Accurate prediction of structural durability requires good knowledge of transport properties of concrete and their evolution over time. The transport properties of concrete vary with age and deterioration caused by loading and exposure conditions. Mechanical loading and environmental attacks, on the other hand, lead to a deterioration of the concrete material. This deterioration, often accompanied by cracking, increases the transport properties (see Figure 1). Very little work has been reported on the effect of cracking on moisture movement and chloride penetration in concrete. Moreover, most of that work is concerned with the fully saturated case [3]. Mechanical loading often leads to the creation of new cracks and/or extension and widening of existing ones. Cracks constitute privileged pathways for water movement and ions transport. Cracking will occur whenever the tensile strain to which concrete is subjected exceeds its strain. Strains may be generated by various basic mechanisms other than mechanical loading such as temperature (restrained expansion or contraction, freezing and thawing), restrained shrinkage and differential settlement of foundations etc.

The present study has been undertaken to shed some light on the effect of cracking on chloride penetration into concrete. Very little information exists in this area. The effects of crack length and crack inclination have been investigated and results compared against the case of uncracked concrete. This allows one to quantify the loss of accuracy by assuming that the original transport properties remain constant throughout the service life of the structure.

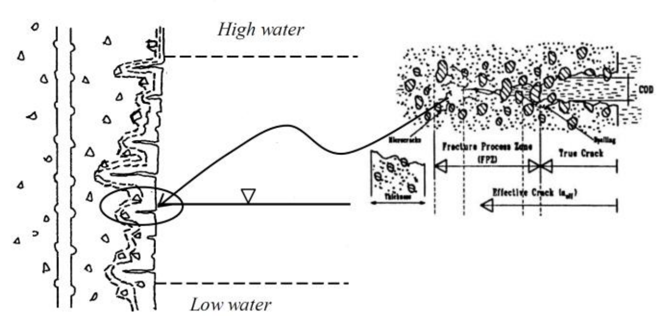

Figure 1. Concrete structures in the splash zone

MODELING MOISTURE FLOW AND CHLORIDES TRANSPORT

I. UNCRACKED CONCRETE

Flow of an incompressible fluid in a saturated rigid porous medium is governed by suitable boundary conditions and the following system of equations

$$\begin{cases} \vec{u} = -\overline{\overline{K}}\,\vec{\nabla} h \quad (Darcy's\ law) \\ c\dfrac{\partial h}{\partial t} + div(\vec{u}) = s \quad (Mass\ conservation\ equation) \end{cases} \tag{1}$$

where $\vec{u}$ is Darcy's velocity, $\overline{\overline{K}}$ is the permeability tensor, *h* is the piezometric head, *c* is the storage coefficient, s is a source/sink term. The piezometric head and pressure are related by $P = \rho\, g\, h + \rho\, g\, z$. Darcy's law is extended to unsaturated porous media by replacing saturated hydraulic conductivity in Equation 1 with a hydraulic conductivity function $K(\theta)$ such that

$$\vec{u} = -K(\theta)\,\vec{\nabla} h \tag{2}$$

where permeability is a function of water content (or saturation). Unsaturated flow is assumed to occur by means of interconnecting fluids inside the pore structure. This concept is correct in pore-pressure ranges where capillary forces dominate. The effective hydraulic conductivity function is given by

$$K(x,h) = \begin{cases} K_s(x)\, K_r(x,h) & if \quad h < 0 \\ K_s(x) & if \quad h \geq 0 \end{cases} \tag{3}$$

where K_r is the relative hydraulic conductivity and K_s the saturated hydraulic conductivity.

Chloride transport is modeled here using a general advective-dispersive equation for transport in variably saturated concrete , treated as a porous medium

$$\frac{\partial \theta^{ma} C^{ma}}{\partial t} = \frac{\partial}{\partial x_i}\left[\theta^{ma} D_{ij}^{ma}\ \frac{\partial C^{ma}}{\partial x_j} - u_i^{ma} C^{ma}\right] \tag{4}$$

where θ^{ma} is the volumetric water content in the matrix, C^{ma} is the concentration of chlorides in the matrix, D_{ij}^{ma} is the dispersion tensor, and u_i^{ma} is the volumetric flux. Mechanical loading on the other hand leads to creation of new cracks and/or extension and widening of existing ones inducing an accelerated penetration rate of ions. Cracks constitute privileged pathways for water movement and ions transport. At this stage, Eq. (1) and Eq. (2) need to be altered to account for this phenomenon. Two approaches can be used: 1- a smeared approach, where Diffusivity and permeability are increased according to the extent of damage in the cracked area , 2- a discrete approach, where a crack is explicitly represented by two surfaces in which flow occurs and an exchange is allowed with the surrounding concrete. This latter approach is summarized in the next section.

II. CRACKED CONCRETE

Among the major mechanisms that need to be accounted for explicitly, when predicting flow and transport within and around a discrete crack, one can mention: various flow types in the fracture, transport of chemicals by advection, dispersion and molecular diffusion within the fracture together with molecular diffusion in the adjacent porous matrix and adsorption on both the fracture lips and within the matrix.

In a simplified approach, discrete cracks can be represented by two parallel walls where flow is governed by the Navier-Stockes equations. Assuming conditions of no slippage on the fracture walls, the velocity distribution across the fracture width is parabolic and given by

$$\vec{v} = \frac{1}{2\mu}\frac{\partial p}{\partial x}(y^2 - by)$$

The average fluid velocity, $\vec{u}_{cr}$, across the crack opening obeys a Darcy-type law

$$\vec{u}_{cr} = -T\,\vec{\nabla} h \tag{5}$$

where *h* is the pressure head and *T* is the transmitivity of the crack which is proportional to the cubic power of the crack width, b

$$T = \frac{\rho\, g}{12\,\mu} b^3 \tag{6}$$

where μ and ρ represent the fluid viscosity and density, respectively, and g is the acceleration of gravity. This law means, that fracture flow can be described by Darcy's law for porous media by using an equivalent hydraulic conductivity. Equation 7, often referred to as the cubic law, is usually derived for the flow in fractures with parallel walls, has been shown to be valid when the walls are not parallel and the width being reduced by the application of stresses. The effects of a variable crack width on the flow in the fracture can be accommodated by using a statistical distribution of widths. For a fracture approximated by m discrete segments with different widths, the fracture transmitivity can be expressed as

$$T = \frac{1}{12}\frac{\rho g}{\mu}\sum_1^m l_i f_i b_i^3 \tag{7}$$

where b_i is the central value of width in the i^{th} interval, f_i is the number of segments of width b_i in the i^{th} interval, l_i denotes the length of the segments. For a width that varies continuously along the fracture, $b=b(s)$, Equation 8 is replaced by

$$T = \frac{1}{12}\frac{\rho g}{\mu} L \int_0^{\infty} b^3 f(b)\, db \tag{8}$$

where *f(b)* is the frequency distribution and *L* is the crack length.

Under partially saturated conditions, the most important questions in determining the flow pattern and travel time through cracked concrete is whether water moves in the fracture or in the matrix. While fractures with large openings will drain relatively easily, water is likely to remain in the small cracks and the matrix. Large pores cannot sustain large capillary suction forces. This can be explained by the nature of the capillary mechanism. Water moisture exchange between matrix and fracture can occur only in the saturated sections and in contact areas. Only the open flow channels with widths smaller than the saturation cutoff opening b_s can contribute to the flow. Therefore, equation 9 can be adjusted under partially saturated condition by limiting the integration to the flow channels which are still saturated inside the fracture

$$T(h) = \frac{1}{12}\frac{\rho g}{\mu} L \int_0^{bc} b^3 f(b)\, db \tag{9}$$

The relative permeability for the crack, defined as the ratio of transmitivity at saturation S to that of saturated condition S=1, is hence, for a lognormal distribution

$$k_r(h) = \tau \frac{\int_0^{b_s} b^3 f(b) db}{\int_0^{\infty} b^3 f(b) db} = \frac{1}{2} Erfc\left(\frac{\log \frac{b_0}{b_c} + \sigma^2 \ln 1000}{\sqrt{2\sigma^2}} \right) \tag{10}$$

The saturation function given by

$$S_w = \frac{\int_0^{bc} b f(b) db}{\int_0^{\infty} b f(b) db} = \frac{1}{2} Erfc\left(\frac{\log \frac{b_0}{b_c} + \sigma^2 \ln 10}{\sqrt{2\sigma^2}} \right) \tag{11}$$

where $\log b_0$ is the mean and σ^2 is the variance of the logarithm of width distribution. Erfc is the complementary error function. The relation between effective permeability and pressure head, as shown in Figure 2, demonstrates that the fracture permeability is very sensitive to suction. If fully saturated, the fracture permeability is twelve orders of magnitude greater than the matrix permeability. With small suctions in the range of –0.1 to –10 m, the discrete fracture permeability decreases drastically. The matrix permeability decreases much more gently than fracture permeability as the pressure head becomes more negative.

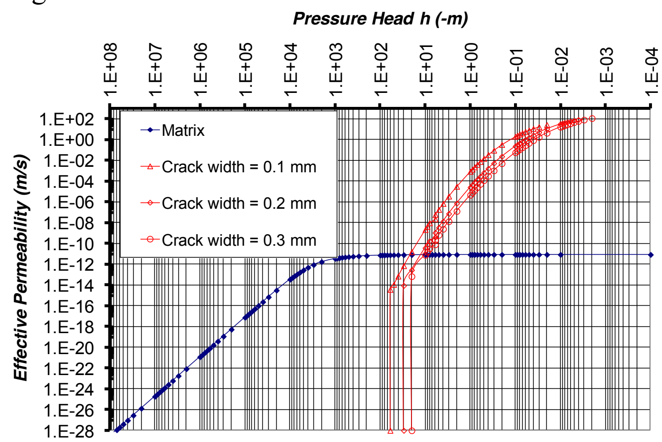

Figure 2. Effective permeability of fracture and concrete

Near fully saturated conditions, the fracture controls the liquid flow. As desaturation, during the drying period, proceeds and the fracture permeability of each discrete fracture becomes less than the matrix permeability, the matrix will control the flow. With in situ suction of over –100 m, fracture flow diminishes and matrix flow dominates.

Transport in variably saturated concrete or through the crack is assumed to be governed by the following advective-dispersive equation

$$\frac{\partial \theta^{fr} C fr^{fr}}{\partial t} = \frac{\partial}{\partial x_i}\left[\theta^{fr} D_{ij}^{fr} \frac{\partial C^{fr}}{\partial x_j} - u_i^{fr} C^{fr} \right] \tag{12}$$

where θ^{fr} is the volumetric water content in the crack, C^{fr} is the concentration of chlorides in the crack, D_{ij}^{fr} is the dispersion tensor in the crack, and u_i^{fr} is the volumetric flux through the crack. This is a generalization of Fick's second law of diffusion because it includes transport by pure molecular diffusion as well as by advection (transport of chlorides by water movement). The dispersion tensor of the crack accounts for both the molecular diffusion as well as kinematic dispersion due to the parabolic profile of the velocity in the fracture. Transport in a fractured concrete element is a coupled phenomenon: the crack is affected by the concentration flux through the walls of the fracture and transport in the matrix is affected by the imposed concentration boundary conditions on the surfaces of the crack. At fully saturated conditions, diffusion in the crack is assumed to be equal to diffusion in water whereas tortuosity and the complicated pore structure of the matrix lead to a lower coefficient of diffusion in the matrix. The transport parameters for the matrix have been measured experimentally.

FRACTURED CONCRETE ELEMENT SUBJECTED TO CHLORIDE IONS PENETRATION

Figure 3 shows a 100x100 mm concrete element endowed with a 30 mm vertical crack, the bottom of which is subjected to alternate wetting and drying cycles. The wetting

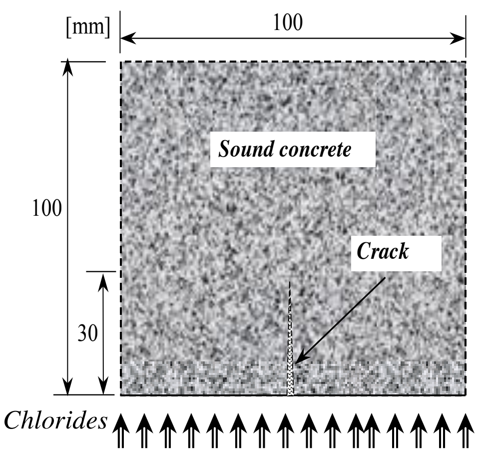

Figure 3. Fractured concrete element and its corresponding FE model

corresponds to a chloride concentration of 13 kg/m3 for 1 week whereas the drying corresponds to a 65 relative humidity for 1 week. The crack opening along the fracture plane is assumed to follow a lognormal distribution with *0.1 mm* average width.

The finite element predictions for chloride penetration after 1, 5, 10, and 15 years of exposure and their comparison with the predictions using Fick's second law of diffusion are shown in Figure 4. As can be seen, the predictions by both methods tend to agree away from the crack. However, as we move closer to the crack location, the discrepancy becomes more important. As expected, the difference is most pronounced at the crack location (section CC). At this location, one can easily see that the chloride ion concentration is much higher than away from the crack or in the case where no cracking exists. A rather sharp decrease is noticed beyond the crack tip (30 mm) where concrete is assumed to be still sound. Table 1 summarizes the material characteristics of the concrete used in the calculations. This corresponds to a medium quality concrete with an apparent coefficient of diffusion equal to $6.2x10^{-11}\ m^2/s$.

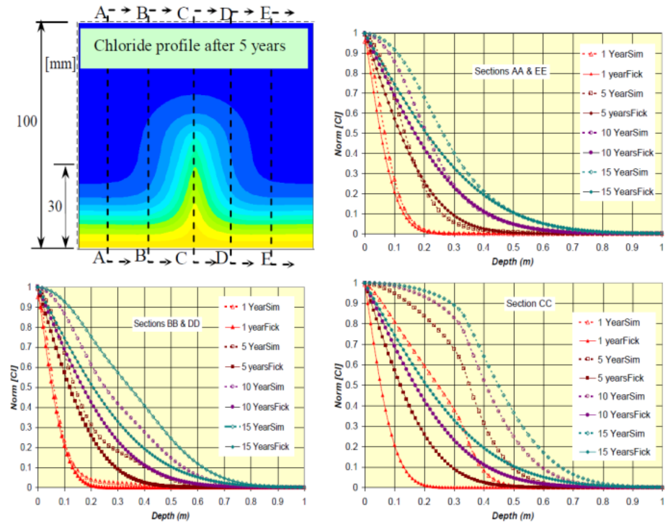

Figure 4. Chloride ions distribution in the fractured element and at various cross sections in the case of a vertical crack.

CONCLUSIONS

Models for predicting moisture movement in a fractured concrete have been presented for both the saturated case as well as the unsaturated case. Near fully saturated conditions, the fracture controls the liquid flow. However, during a drying process, the large fractures will be drained easily and liquid water will remain only around the contact areas in the fracture plane. The wetted regions centered around the contact areas provide bridges for liquid water to flow across the fracture plane from one matrix block to its neighboring matrix blocks making the matrix control the liquid flow.

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