CHLORIDE ION INGRESS IN MARINE CONCRETE STRUCTURES: A DISCRETE REPRESENTATION OF CRACKING

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INTRODUCTION

Concrete has been used as the building material of choice in marine structures due to its good durability in chloride laden environments. 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 investigated. The effect of discrete representation of cracking and exchange with the surrounding matrix on the chloride ingress has been investigated.

UNCRACKED CASE

Prior to any major crack creation, concrete is considered as a porous material. Chloride transport is classically modeled using Fick's second law of diffusion or one of its time dependent variants

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left[D(x,t)\frac{\partial C}{\partial x} \right] \tag{1}$$

where C is the concentration of chlorides and D is the diffusivity. This equation assumes that transport is governed by pure diffusion in the material. A more general equation for transport in variably saturated concrete is governed by the following advective-dispersive equation

$$\frac{\partial qC}{\partial t} = \frac{\partial}{\partial x_i}\left[qd_{ij}D\frac{\partial C}{\partial x_j} - q_i C \right] \tag{2}$$

where d_{ij} is the Chroniker symbol, D is the dispersion coefficient, and q_i is the volumetric flux. It has been found that Eq. (1) and Eq. (2) give comparable results within the range of usual concrete permeabilities. However in the case of very low quality concrete (very high permeability) and relatively high-pressure gradients, Eq. (2) is no longer able to accurately predict the final distribution of chloride ions. This is mainly due to the fact that chlorides being transported by the movement of water (advection) are not accounted for, in which case, Eq. (2) is more appropriate. 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.

Keywords: Chloride transport, concrete, cracking, diffusion

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DISCRETE CRACK MODEL

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.

The discrete fracture is represented by two parallel walls where flow is governed by the Navier-Stockes equations. The velocity distribution across the fracture width is parabolic. The average fluid velocity, $\vec{U}$, across the crack opening obeys a Darcy-type law:

$$\vec{U} = -T\,\vec{\nabla} h \qquad (3)$$

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

$$T = \frac{rg}{12m} b^3 \qquad (4)$$

where m and r represent the fluid viscosity and density, respectively, and g is the acceleration of gravitation.

Flow of water in the matrix is generally negligible compared water flow in the crack. Therefore it is assumed that the transport mechanism in the matrix is pure molecular diffusion. Transport of chloride ions through the crack and the surrounding concrete matrix is, therefore, given by

$$\begin{cases} \dfrac{\partial C_{fr}}{\partial t} = \vec{\nabla}\left(\overline{D}\,\Delta C_{fr} - \vec{U}\,\vec{\nabla} C_{fr}\right) + a_w\, w\, D_p \dfrac{\partial C_m}{\partial z} \quad \textit{in the fracture} & (5) \\[2ex] \dfrac{\partial C_m}{\partial t} = D_p \Delta C_m \quad \textit{in the matrix} & (6) \end{cases}$$

where C_{fr} is the ions concentration within the crack, C_m is the ions concentration within the matrix, a_w is the specific surface (=2/*b*), D_p is the diffusion coefficient in the matrix, w is the porosity of the matrix. The dispersion tensor $\overline{D}$ accounts for both the molecular diffusion as well as kinematic dispersion due to the parabolic profile of the velocity in the fracture. Eq. (5) and Eq. (6) are coupled: transport in 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.

Eqs. (5) and (6) have been solved numerically using the finite element method for two types of boundary conditions. A constant concentration $C(x=0,t)=C_0$ *for* $t>0$,and a step function defined by $C(x=0,t)=C_0$ *for* $t \in [0, T_0]$ and $C(x=0,t)=0$ *for* $t > T_0$. It has been observed that the fraction of chloride ions penetrating the matrix increases with increasing matrix diffusion coefficient leading to lower concentration maxima in the fracture. When imposing the step boundary condition, the matrix starts progressively losing to the crack the ions that had previously penetrated it after T_0 , leading to increasing concentration levels with increasing matrix diffusivity. This phenomenon cannot be reduced to a simple advection-dispersion problem in the fracture without an explicit account for matrix diffusion. The smaller the crack opening, the more sensitive the matrix diffusion in the fracture is.