論文 Prediction of Cracking Effect on the Penetration of Chloride Ions in Reinforced Concrete

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ABSTRACT: Durability in harsh environments, which is controlled by the phenomena of mass transport within concrete (such as chlorides, acids etc.), has been identified as one of the major parameters controlling the long-term performance of concrete structures. Mechanical loading, which usually leads to creation of new cracks and/or extension and widening of existing ones, induces a higher penetration of chemicals. Beyond a certain concentration threshold around rebar, corrosion occurs and the load bearing capacity of a structural member may be reduced. This paper presents a method for modeling the long-term performance of RC beam subjected to the simultaneous action of external loading and a chloride laden environment. The effect of cracking on the penetration of chloride ions was studied.
KEYWORDS: Service life, chloride ingress, integrated analysis, damage mechanics, reinforced concrete beam, corrosion

1. INTRODUCTION

Service life prediction has emerged, over the last few years, as a major task in the design of concrete structures. The main cause of distress of concrete structures in marine environments is related to reinforcement corrosion due to chloride ions penetration. The corrosion problems should be prevented by appropriate construction of new structures and by providing durable repairs to corroding ones. Such a goal could be best achieved through a rational integration of durability and structural designs [1,2].

The ingress of chloride ions does not depend only on concrete transfer properties, but also on the loading applied and the state of damage as characterized by cracking. It is well known that under high external loading, concrete can be significantly damaged. The effect of this damage on chloride penetration and the long-term performance of RC beams is investigated in this paper.

2. COUPLING OF EXTERNAL LOADING AND CHLORIDE INGRESS

Concrete structures are subject to the simultaneous action of mechanical loading and environmental attacks throughout their lifetime. Each of these actions leads to a deterioration of the concrete material [3].

Water movement in concrete is governed by the following partial differential equation in the case of a two dimensional saturated or unsaturated flow

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^A \frac{\partial h}{\partial x_j} + K_{iy}^A\right)\right] \quad (1)$$

where θ is the volumetric water content, h the pressure head, x_i $(i=1,2)$ are the spatial coordinates, t is time, K_{ij}^A are components of a dimensionless anisotropy tensor K^A, and K is the hydraulic conductivity function.

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The chloride transport under transient water flow conditions in a partially saturated concrete is given by

$$\frac{\partial \theta c}{\partial t}=\frac{\partial}{\partial x_i}\left[\theta \delta_{ij} D \frac{\partial c}{\partial x_j}-q_i c\right] \tag{2}$$

where c is the concentration of chlorides, δij is the Chroniker symbol ($\delta ij=1$ if $i=j$ and $\delta ij=0$ otherwise), D is the diffusion coefficient, and q_i is the volumetric flux.

The physical phenomena of nucleation, propagation and coalescence of cracks are represented in the framework of continuum mechanics by a scalar damage variable d [6]. This model is based on the effective stress concept defined by:

$$\sigma=\Lambda_0(1-d):\varepsilon \tag{3}$$

where σ is the stress, ε is the strain and Λ_0 is the initial rigidity tensor, : denotes the contracted tensorial product. The mechanical characteristics change with the extent of damage as follows

$$\begin{cases} E=E_0(1-d) \\ v=v_0 \end{cases} \qquad \begin{cases} d=0 & \rightarrow \text{Sound concrete} \\ d=1 & \rightarrow \text{Fractured concrete} \end{cases} \tag{4}$$

where E is Young modulus and v Poisson coefficient. The evolution of d is specified according to a formalism very similar to the theory of plasticity where the damage threshold $\chi(d)$ is given by

$$f(\varepsilon_{av},\Lambda)=\varepsilon_{av}-\chi(d)=0 \tag{5}$$

with $\varepsilon_{av}=\frac{1}{|\Omega(x)|}\int_V \tilde{\varepsilon}(s)\,w(s-x)\,dv \quad , \quad \tilde{\varepsilon}=\sqrt{\sum_i \langle\varepsilon\rangle_+^2}$

$$w(s-x)=\begin{cases} Exp\left[\left(\frac{-k|s-x|^2}{l_c}\right)\right] & \text{if} \quad |x-s|\le l_c \\ 0 & \text{if} \quad |x-s|>l_c \end{cases}$$

ε_i is the i^{th} principal strain, $\Omega(x)$ is the representative volume element at point x, V the volume of the structure, $w(s-x)$ is a weighting function and l_c the characteristic length of the material.

An empirical equation relating the corrosion rate q to the availability of water, oxygen and chlorides in concrete has been adopted in this study [4]

$$q=k(\alpha_0+aC)\phi\, S\, C_{O_2}\, Exp\left\{-\frac{E}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right\} \tag{6}$$

where k is a conversion factor, α_0 the referential rate coefficient, a coefficient for sensitivity of chloride effect, ϕ porosity, S degree of saturation, C_{O_2} concentration of oxygen in the pore solution phase, T temperature, R the universal gas constant, and E the activation energy.

Corrosion-induced cracking is accounted for by imposing a corrosion induced-displacement due to the expansion associated with rust formation. The volume of rust was assumed to be 3 times the volume of the original steel. Transport properties are increased as a result of cracking caused by the combined action of external loading and corrosion-induced pressure around the rebar. Prior to any cracking in concrete ($d=0$), permeability and diffusion remain equal to the assumed ones for sound concrete, K_0 and D_0 respectively. Once a discrete crack has developed in a certain region ($d=1$), both permeability and diffusion are assumed to take the following ultimate values $K_u=10^{-3}m/s$ and $D_u=D_w=1.8510^{-9}\,m^2/s$. K_u is assumed to represent the permeability of a very damaged concrete [5], and D_w is the diffusion coefficient in water. For intermediate situations, corresponding to the case of microcrack initiation and propagation ($0<d<1$), transport properties are increased linearly from their initial values to ultimate ones. Due to a lack of experimental evidence, a linear relationship has been assumed.

3. LONG TERM PERFORMANCE OF RC BEAM

Figure 1 shows the dimensions of a beam together with the loading, support conditions and the reinforcement. The initial load deflection response of the beam was computed before exposing it to any chloride penetration in order to predict its original behavior. This is represented on Figure 2 as the curve corresponding to corrosion. After this, the beam is subjected to the combined action of a constant mechanical load equal to 400 kN (60% of ultimate load) and 13 kg/m^3 chloride concentration at the bottom. The structure is assumed to stay in service for 50 years during which rehabilitation works will be conducted just before the first time to corrosion initiation is reached. The following tasks are assumed to take place: the chloride ions are removed using electrochemical techniques and surface coating is applied. The quality of the coating to apply will be determined according to the length of time needed to protect the beam from any chloride ingress so that its planned service life can be achieved. The constitutive properties adopted in this study are shown in Table 1. The chloride threshold for corrosion to occur has been assumed to be 1.1 kg/m3.

Figure 2 shows that rebar corrosion has a significant impact on the long-term flexural performance of the beam under a constant and relatively high load (60 % of ultimate load). There was a loss in both load carrying capacity and deformation capacity.

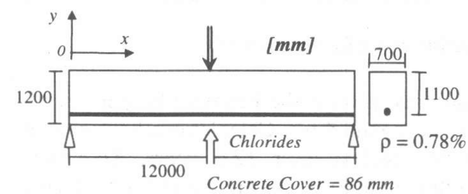


Figure 1. Schematic representation of RC beam

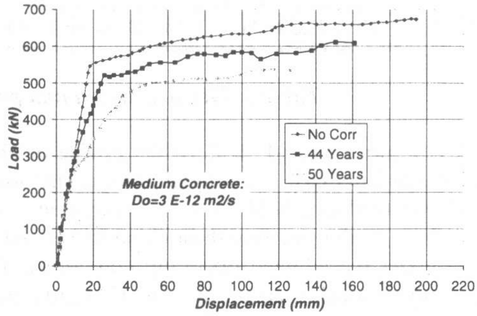
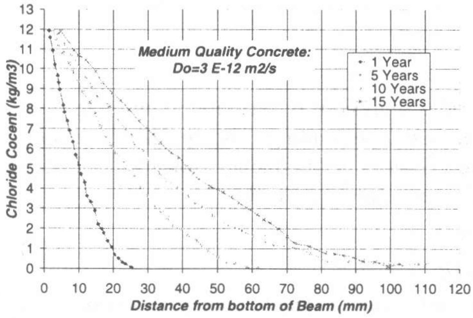
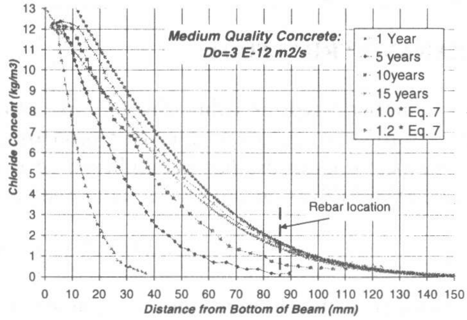


Figure 2. Load deflection relationship



a) Numerical Solution (No Loading)



b) Numerical Solution (with Loading)

Figure 3. Chlorides Distribution at Midspan

		Mixture design and measured diffusion coefficient				
Concrete Quality	*w/c*	*Cementitious Factor (kg/m^3)*	*Silica Fume replaced (%)*	*Slump (mm)*	*Air (%)*	*Do ($x10^{-12}$ m^2/s)*
Low	0.50	302	0	165	7	4.97
Medium	0.45	325	8	133	7.5	3.01
High	0.37	390	4	178	7.8	0.98

		Corrosion parameters			
k	α_0 *(cm/day)*	*a*	C_{O_2} *(g/cm^3)*	φ *(%)*	*T (K)*
3.48	0.15	16.9	$9.5x10^{-6}$	10	293

	Material characteristics		
Concrete		*Steel*	
Tensile Strength (MPa)	2.58	Yield Stress (MPa)	400
Compressive Strength (MPa)	30.00	Young Modulus (GPa)	200
Young Modulus (GPa)	2.64	Rebar Diameter (mm)	28
At = 1.25 ; Bt = 1200; Ac = 1.25 ; Bc = 3E4; $\chi(0)$=1.5 E-4		Number of Rebars	10

Table 1. Mixture design and parameters used in the analysis

Figures 3a and 3b show the profile of chloride ions through the beam without and with loading. In latter case cracking due to external loading is accounted for. Calculations have shown that the critical threshold to rebar corrosion would be reached after 12.6 years. To ensure the safety of the structure throughout its service life rehabilitation works are carried out after 11 years under the adopted operating conditions. The coating is assumed to protect the structure from any chloride penetration for 17 years. After this time the coating is assumed to have completely failed and the beam is exposed to the same environmental conditions as at the beginning. Therefore, the critical chloride content to cause corrosion will be reached after 40.6 years (11+17+12.6).

4. PARAMETRIC STUDY

Rebar corrosion being directly linked to chlorides ingress, it is very important to account properly for the increase in transport properties under external loading. The specified constant environmental exposure has been chosen so that the classical error function solution to Fick's second law of diffusion can give a good prediction. This equation is given by

$$C(x,t) = C_o\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right] \quad (7)$$

where $C(x,t)$ is the chloride concentration at depth, x, and at time t. The boundary conditions that satisfy eq. 7 are for an instantaneous and constant application of surface chloride concentration, C_o, where t is the time since the application of C_o. However, eq. 7 assumes that both C_o and D

are constants and do not depend on either position, time, or chloride concentration. A number of finite element simulations were conducted to assess the effect of cracking on the chloride ingress into the beam and the results were compared with the predictions obtained using the widely used analytic solution (i.e. eq. 7). A high quality concrete and a low quality concrete together with three methods of analysis were considered under a severe loading (80% of ultimate load). Figures 4 and 5 show that the analytical predictions of chloride distribution at midspan and the finite element prediction when no cracking is considered are very close. However, when cracking due the assumed loading is considered we can see that the finite element prediction of ions ingress is significantly different from the one predicted by eq. 7.

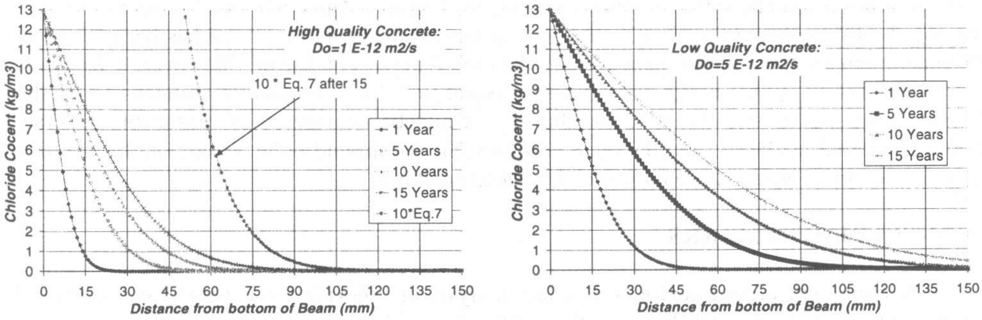


Figure 4. Analytical Solution

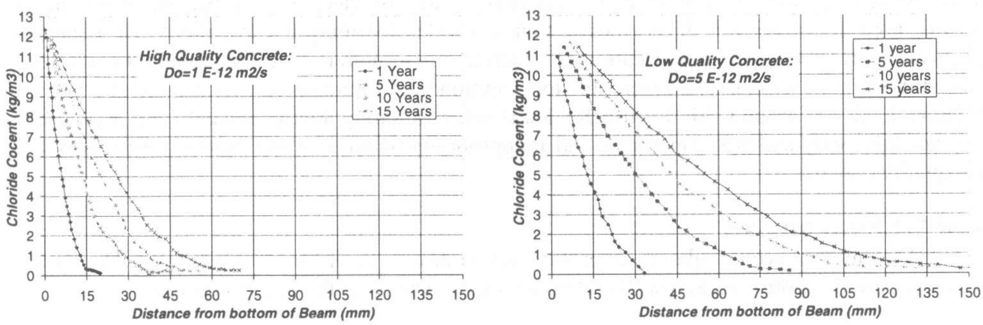


Figure 5. Finite Element Method (No Cracking)

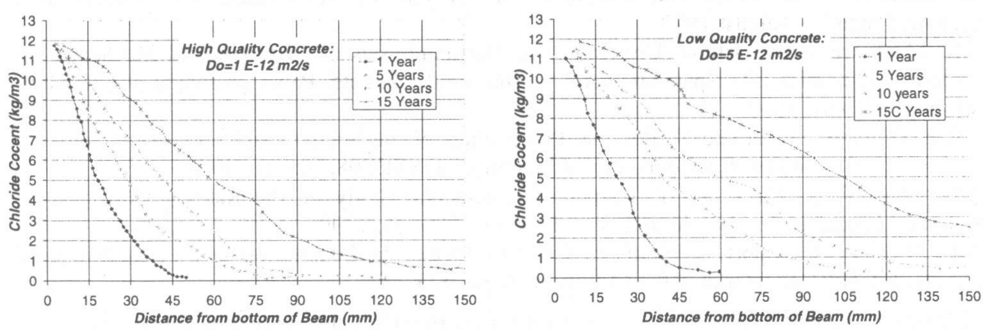


Figure 6. Finite Element Method (With Cracking)

As can be seen in Figures 4 and 6, under the assumed exposure conditions, eq. 7 will never be able to predict the ions penetration, no matter what safety factor is adopted (a safety factor equal to 10 has been used in Figure 4 with the 15 years chloride distribution as predicted by eq. 7). This shortcoming is even more noticeable in the case of high quality concrete with low diffusion coefficients where the chloride profiles in the uncracked case are much lower than those associated with severe loading. This might lead to a significant overestimation of the service life, even if using very high safety factors. Thus, under severe conditions it is necessary to account properly for the effect of cracking on the penetration of chlorides

Figure 3, on the other hand, shows that under the same environmental conditions, but subject to a lower loading (60% of ultimate load), eq. 7 gives comparable predictions to the ones given by the finite element method (when no cracking is accuonted for) and has been found to still under-estimate the chloride penetration when cracking is considered. However, it has been observed in this study that using a safety factor equal to 1.2 was enough to compensate for the underprediction. Consequently, it seems that eq.7 could be considered as reasonably accurate when the external loading is kept below a certain value (< around 60% of ultimate load) and a safety factor can be used to account for load induced cracking.

5. CONCLUDING REMARKS

A numerical procedure for a coupled analysis of chloride ions ingress and structural response was presented. Usefulness of this approach is illustrated by the computation of the performance of a RC beam in a chloride laden environment. It has been possible to account for the effect of concrete damage on its transport properties and vice-versa. In particular, it has been shown that the flexural strength of the RC beam is greatly affected by the rebar corrosion due to chloride ingress. Moreover, it is shown that chloride distribution throughout the beam is significantly affected by the deterioration of concrete due to high external loading and corrosion-induced cracking. The classical error function solution was found to be suitable for the case of moderate loads (< around 60 % ultimate load) when a safety factor equal to 1.2 was used. However this analytical solution was found inappropriate under a severe loading, especially for high quality concrete.

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