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## **NUMERICAL STUDY OF CHLORIDE INGRESS IN CONCRETE: EFFECT OF EXPOSURE CONCENTRATION**

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### **Abstract**

The corrosion process is usually described into two periods that model the service life of the reinforced concrete structures such as bridges and other structures exposed to marine environments: 1) the initiation period and 2) the propagation period. The initiation period is the time required for aggressive substances (e.g., carbon dioxide, chlorides, etc.) to penetrate from the environment into the cover concrete until critical chloride ion concentration is reached at the bar reinforcement to initiate the corrosion process. In the present paper, a numerical model is developed to study the effect of the exposed concentration of chloride on the initiation period of the corrosion. This initiation period is modelled by considering physico-chemical interactions between the ions and the solid components of the concrete. Several examples of application of the model are presented to show the interest of studying the influence of the exposure concentration of chloride ions on the penetration depth in the concrete. The effects of chloride binding, chemical activity of the pore solution and electrostatic interactions are also presented.

### **1. Introduction**

The corrosion of reinforcement concrete structures due to the penetration of chloride ions is an important problem in civil engineering. When the concentration of chloride ions is critical, the corrosion of the steel will start and the service life of the concrete structure will reduce. In United Kingdom, this pathology of concrete is the first cause of degradation of bridges. This degradation depends on the exhibition class [1]. According to the norm NF EN 206-1 there are 18 exhibition classes. These classes depend on the exposure weather and on the concentration of chloride ions which penetrate in the concrete structure such as sea water

attack (XS class) and de-icing salt (XD class). When concrete is submerged totally in water, chloride ions will penetrate by diffusion only such as in the submerged bridge pier. When concrete is partially saturated and exposed to wetting and drying cycles chloride ions will penetrate by diffusion and convection.

The transport of chloride ions is well studied in the literature and many models are available for the simulation of chloride ions in saturated [2-3] and unsaturated concrete [4-5]. The ingress of chloride ions is significant in a marine environment and also when using salt spray. For this reason, this paper aim to enhance the signification of the penetration depth of chloride ions taking into account the exposure weather and the exposure concentration of chloride ions. This study will show us the effect of the initial concentration of chloride ions on the service life of concrete structure and on the initiation of corrosion of reinforced concrete. In order to study the unsaturated case, this work could be considered as an extension or a continuation of the Benchmark WG2.4 “Macroscopic model to predict chloride content in saturated concrete” carried out in the framework of Cost action.

After this introduction, the used numerical model is presented in section 2. It considers the physico-chemical mechanisms of the penetration of chloride ions. The influence of the exposure concentration of chloride ions on the service life of concrete and on the penetration depth of chloride ions are shown in section 3. The conclusion of this work follows in section 4.

## 2. Model of chloride transport in unsaturated concrete

The chloride penetration is a complex physical and chemical process. In our model, this process is divided into four parts: transport of chloride by 1) diffusion, 2) convection, 3) ions interaction and 4) chemical activity of ions. The flowchart of the model is illustrated in Fig.1. The governing equations can be given by:

$$J_i = -D_i \left[ \text{grad}C_i + \frac{z_i F}{RT} C_i \text{grad}\Psi + C_i \text{grad}(\ln Y_i) \right] + C_i V \quad (1)$$

Where  $D_i$ ,  $C_i$ ,  $z_i$  and  $Y_i$  are respectively the effective coefficient of diffusion ( $\text{m}^2/\text{s}$ ), the concentration ( $\text{mol} \cdot \text{m}^{-3}$ ), the valence and the coefficient of activity of the ion  $i$ .  $F$  the Faraday constant ( $96485,309 \text{ C} \cdot \text{mol}^{-1}$ ),  $R$  the ideal gas constant ( $8,3143 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$ ),  $T$  the temperature (K),  $\Psi$  the electrostatic potential (V) and  $V$  the velocity of water (m/s).

To take into account the effect of water content, the coefficient of diffusion of ions is assessed by Buchwald's work [6] for the ions in the pore solution.  $D_i$  depends on the evolution of the porosity  $\varepsilon$  and on the saturation degree  $S_e$  which is linked to water content volume  $W$ . The equation is expressed as follows:

$$D_i = D_i^{\text{sat}} \left( \frac{W}{\varepsilon} \right)^\lambda \quad (2)$$

Where  $D_i^{\text{sat}}$  is the coefficient of diffusion of ions in saturated concrete ( $\text{m}^2/\text{s}$ ) and  $\lambda = 6$ .

The model adopted for the humidity transport can be derived as follows:

$$\frac{\partial S_e}{\partial t} = - \frac{K_e K_{re}}{\varepsilon \mu_e} \frac{\partial P_c}{\partial S_e} \text{grad}S_e + \frac{R_a D_{va}}{\rho_e} \frac{\partial \rho_v}{\partial S_e} \text{grad}S_e - \frac{M_{H_2O}}{\rho_e} \frac{\partial S_{CaOH_2}}{\partial t} \quad (3)$$

Where  $D_{va}$ ,  $\mu_e$ ,  $M_{H_2O}$  and  $\rho_e$  are, respectively, the coefficient of diffusion of water vapor, the viscosity, the molar mass and the density of water.  $S_{CaOH_2}$  is the solid content of Portlandite during the transport of chloride ions.  $P_c$  is the capillary pressure (atm) calculated from  $\varphi(W)$ , which describes sorption and desorption isotherms which relate the water content to the humidity. The isotherms can be derived from experimental results depending on the type of concrete and on wetting-drying cycles

$$P_c = -\rho_e \frac{RT}{M_v} \ln \varphi(W) \quad (4)$$

$K_e$  is the intrinsic permeability ( $m^2$ ). It depends on the microstructure of concrete and it was assessed from its initial porosity  $\varepsilon_0$  through Genuchten's equation [7] and  $K_{re}$  is the relative permeability ( $m^2$ ) [8].  $R_a$  is the resistance to the air (Thiery's work [9] based on Millington's study [10])

$$K_e = K_e^0 \left(\frac{\varepsilon}{\varepsilon_0}\right)^2 \left(\frac{1-\varepsilon_0}{1-\varepsilon}\right)^2 \quad (5)$$

$$K_{re} = (S_e)^{0.5} [1 - (1 - (S_e)^{1/0.34})^{0.34}]^2 \quad (6)$$

$$R_a = (\varepsilon)^{2.74} (1 - S_e)^{4.8} \quad (7)$$

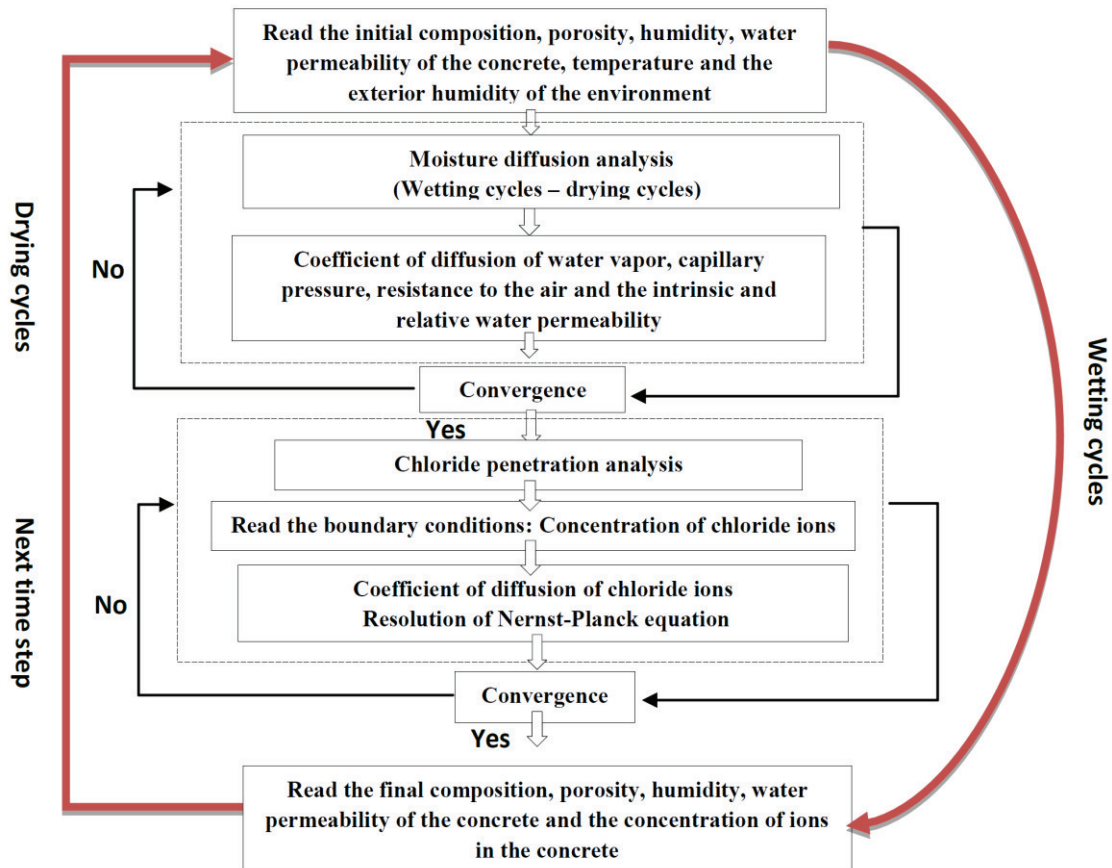


Figure 1: Flowchart of the numerical model.

### 3. Results and discussion

The discretization approach for 1D domain had been to model the ionic transport process of concrete. The finite difference method is used to solve the above equations (1-7).

#### 3.1 Concrete composition, input data and boundary conditions

The concrete mixture used in this study has the composition described in Tab.1 [11].

Table 1: Composition of the concrete specimen.

Concrete M30CV	Value
Gravel 5/12.5	565 Kg/m <sup>3</sup>
Sand 0/5	864 Kg/m <sup>3</sup>
Cement	436 Kg/m <sup>3</sup>
Fly Ash	223 Kg/m <sup>3</sup>
Silica fume	95 Kg/m <sup>3</sup>
Water/Binder	0.74

This concrete is selected from the literature because the input data and the parameters needed in the model are available. The concrete properties and the input data needed for the model are listed in Tab.2. The sorption and desorption isotherms are presented in the Bouny's works [11].

Table 2: Input data of the numerical model.

	Value
Water porosity	0.128
Density of concrete	2349 Kg/m <sup>3</sup>
Effective coefficient of diffusion of chloride ions	2.17 E-13 m <sup>2</sup> /s
Water permeability	4 E-21 m <sup>2</sup>

In order to take into consideration the interaction between chloride ions and the cement paste of the concrete, binding isotherms were measured. The results show that a Langmuir isotherm can be used to link free and bound chlorides:

$$C_{cl,b} \text{ (mol/m}^3\text{)} = \frac{0.000025C_{cl,f}}{1+0.0006C_{cl,f}} \quad (8)$$

The concrete specimen (50 mm) is initially partially saturated ( $S_e^0 = 80\%$ ) and then exposed to chloride attack (0.5 mol/L) under 6h/6h of wetting and drying cycles ( $S_e^{t>0} = 92\%$  wetting,  $S_e^{t>0} = 60\%$  drying,  $T=23^\circ\text{C}$ ).

### 3.2 Chloride transport validation in concrete under cyclic drying-wetting conditions

Fig. 2 shows the profile of chloride ions after an exposure period of 10 years with 6h/6h of wetting and drying conditions. It is clear from the results that the model can predict well the penetration of chloride ions obtained experimentally. We can also note the convection zone is identified. This profile is the result of eq.1 considering chloride ions.

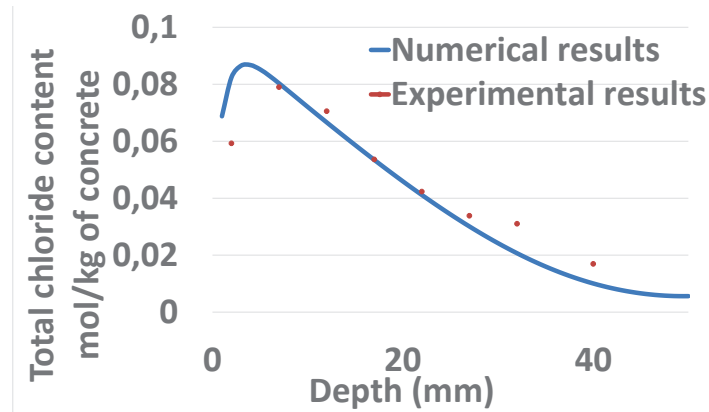


Figure 2: Validation of the model to predict the penetration of chloride ions in the concrete.

### 3.3 Influence of the exposure concentration on the chloride penetration and on the service life of concrete

In order to show the influence of the exposure concentration (0.5-1-2-3 mol/L) on total chloride concentration, a number of simulations are presented in Fig.3 and Fig.4. The numerical model simulates the profile of chloride ions fixing all the parameters and changing only the exposure concentration. These figures show clearly that when the concentration of chloride ions on the surface increases, the penetration depth of chloride increases also due to the high amount of chloride ions. We have to note that the convection zone occurs whatever the chloride concentration. This is due to the convection effect which accelerates the penetration of chloride ions.

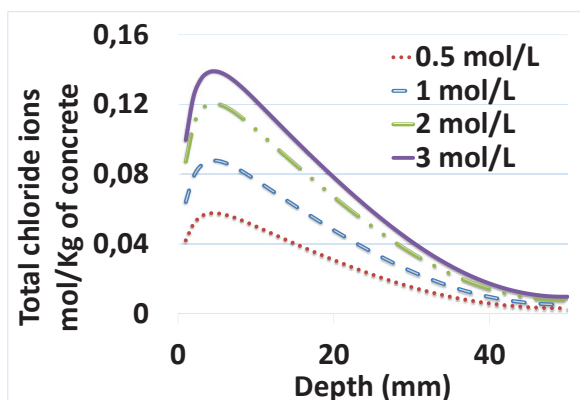


Figure 3: Influence of the exposure concentration on the chloride penetration into concrete.

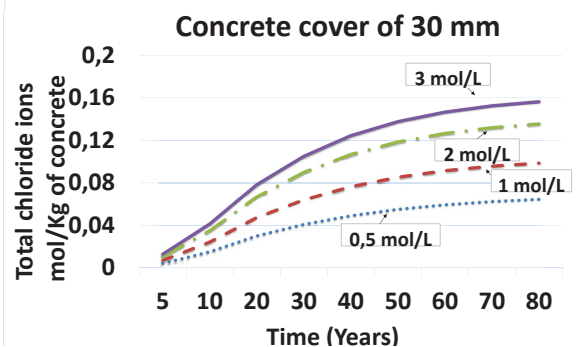


Figure 4: Influence of the exposure concentration on the initiation stage of corrosion.

The numerical model simulates the profile of chloride ions after 80 years of time exposure. For every 10 years the concentration of chloride ions at  $x=30$  mm is plotted in Fig.4 shows clearly that for a concrete cover of 30 mm and after 50-80 years, the initiation stage of corrosion is accelerated when the exposure concentration increases. Finally, as expected, when the chloride content is important (de-icing salt) the corrosion initiation is accelerated.

#### 4. Conclusion

This study is focussed on the study of the effect of exposure concentration on chloride ingress in concrete. The main conclusions that can we drawn are;

- 1- To highlight the convection zone, the coupling of chloride and humidity ingress is required.
- 2- When the concentration of chloride ions is more important on the surface, the initiation time of corrosion is increased.
- 3- The numerical predictions of the penetration of chloride ions are compared with a set of experimental results for unsaturated concrete. It was clear that the experimental results support the validity of the model.

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