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Combined effect of carbonation and chloride ingress in concrete

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HIGHLIGHTS

- A comprehensive model for the combined carbonation and chloride ingress in concrete is developed.
- The effect of CSH is directly considered for the estimation of the degree of carbonation.
- The changes of the pore structure and the binding capacity are considered for the combined action.
- The corrosion initiation can be accelerated significantly by the combined mechanism.

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ABSTRACT

The combined effect of carbonation and chloride ingress in concrete is studied in this paper. Based on the change of the pore structure and the chemical equilibrium, a comprehensive model is proposed for this problem. A coupled simulation of the transports of carbon dioxide, chloride ions, heat and moisture is carried out. Several sets of experimental data were compared with the prediction by the numerical model developed in this paper, for its verification. Parametric study shows that the differences between the combined mechanism and the independent mechanisms are significant in many aspects.

1. Introduction

The corrosion of reinforcement due to the penetration of chloride ions and the carbonation of concrete is an important problem which reduces the durability of reinforced concrete structures. Once the chloride concentration around the surface of the steel reinforcement exceeds a certain threshold concentration, or the pH value of the concrete pore solution decreases to a threshold value due to carbonation reaction, the steel reinforcement will undergo the so-called depassivation process [1–3]. With the intrusion of oxygen, electrochemical reactions occur generating corrosion products on the surface of the steel reinforcement. This results in cracking of the concrete cover due to the swelling pressure of the corrosion products [4,5]. Of course, the cross sectional area of the reinforcement decreases because of the corrosion mechanisms. Therefore, it is important to develop a tool to predict the depassivation mechanisms of steel reinforcement accurately for durability design and pre-planning and maintenance of RC structures. The time-dependent load capacity of a reinforced concrete structure should be assessed by taking into account the growth of the corrosion layer within the cross section of the reinforcements. This subject is certainly important to study, and possible to incorporate. However, we focus only on the initiation of the corrosion in this combined mechanism in this paper.

The transport of chloride ions causing the depassivation of steel reinforcement in concrete is well studied and a number of models are available for the simulation of the process [1,6–11]. Some of them studied the influence of initial cracks in concrete [12–15] and the effect of loading on chloride transport [16,17]. In the literature [18–20], numerical modeling of the entire process of concrete corrosion damage was proposed, in which physical and electrochemical model can be coupled with cracking mechanical model. The corrosion of reinforcement caused solely by chloride ingress has been sufficiently studied and is well understood.

The ingress of chloride ions is often significant in a marine atmospheric environment, where the supply of chloride ions due to salt spray and the carbonation of concrete can occur simultaneously [21]. For instance, the entrances of cross-harbour tunnels are subjected to severe salt spray conditions, and at the same time

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Nomenclature

B_T heat transfer coefficient of concrete surface
B_c chloride transfer coefficient of concrete surface
B_h humidity transfer coefficient of concrete surface
$C_{CO_2,b}$ molar concentration of carbon dioxide on concrete surface
C_{CO_2} molar concentration of carbon dioxide in the gas phase of pore
C_{CSH} molar concentration of the calcium silicate hydrate (CSH) in concrete
C_{bc} content of bound chloride
$C_{ch,d}$ and $C_{ch,s}$ molar concentration of dissolved and solid $Ca(OH)_2$, respectively
$C_{fc,b}$ chloride concentration on concrete surface
$C_{fc,env}$ chloride concentration of the surrounding environment
C_{fc} content of free chloride
C_{tc} content of total chloride
C_{th} threshold chloride content of non-carbonated concrete
C_{th}^{car} threshold chloride content considering the influence of carbonation
$D_{CO_2}^{car}$ diffusion coefficient of carbon dioxide in concrete
D_{fc} chloride diffusion coefficient of non-carbonated concrete
D_{fc}^{car} diffusion coefficient of chloride considering the influence of carbonation
D_h^{car} diffusion coefficient of moisture considering the influence of carbonation
FA ratio of cement replacement by fly ash
I_h internal source of heat
I_{CSH} rate of consumption of carbon dioxide due to the reaction with CSH
I_{ch} rate of consumption of carbon dioxide due to the reaction with dissolved $Ca(OH)_2$
I_d dissolved rate of solid $Ca(OH)_2$
I_{rc} source term reflecting the release of the free chloride ions from the Friedel's salt due to carbonation
I_{w_e} pore water generated by carbonation reaction
$M(\cdot)$ molar mass of the substance given in the round brackets
P_{CO_2} volume fraction of carbon dioxide in the environment
T_b temperature of concrete surface
T_{env} temperature of the surrounding environment
$[C_{CSH}]_0$ initial molar concentration of the CSH in concrete
$[C_{CaO}]_0$ initial molar concentration of the total calcium oxide in concrete
$[C_{ch,d}]_0$ initial molar concentration of the dissolved calcium hydroxide before carbonation
ΔV_{ch} and ΔV_{CSH} molar volume change of $Ca(OH)_2$ and CSH after reacting with CO_2, respectively
$\Delta\phi_c$ ultimate reduction of the porosity after carbonation
Ω tortuosity of concrete
Ω_0 initial tortuosity of concrete
α_L and β_L parameters for Langmuir isotherm
α_c degree of carbonation
$\alpha_{L,c}$ α_L parameter for Langmuir isotherm corrected for carbonation
δ constrictivity of concrete
δ_0 initial constrictivity of concrete
κ correction factor of vapor phase water generated by carbonation
λ thermal conductivity
$\boldsymbol{J}_{CO_2}$ flux of carbon dioxide
$\boldsymbol{J}_{ch,d}$ flux of hydroxide ions
$\boldsymbol{J}_{fc,b}$ flux of chloride ions on concrete surface
$\boldsymbol{J}_{fc}$ flux of free chloride ions
$\boldsymbol{J}_{h,b}$ flux of humidity through the concrete surface
$\boldsymbol{q}_b$ heat flux through the concrete surface
$\bar{r}_p$ dimensionless size of peak radius
$\bar{r}_{p,0}$ dimensionless parameter of peak radius before carbonation
$\bar{r}_{p,c}$ dimensionless parameter of peak radius after carbonation
ϕ current porosity of concrete
ϕ_0 porosity of non-carbonated concrete
ϕ_{hc} porosity of hardened binder
ϕ_{w_e} volume fraction of evaporable pore water
ρ_{CO_2} gas density of carbon dioxide
a/b and w/b aggregate-to-binder ratio and water-to-binder ratio
b binder content per unit volume of concrete
c_q specific heat
d reduction factor of the binding capacity of chloride ions due to carbonation
$f_c(w/b)$ and $f_c(FA)$ influence functions of water-to-binder ratio and fly ash replacement ratio on the change of peak radius due to carbonation
$f_h(w/b)$ influence function of water-to-binder ratio on estimating the peak radius size of non-carbonated concrete
$f_p(\Omega,\delta)$ influence function of the change of the pore structure on the diffusion coefficients of chloride ions and moisture
h_b relative humidity of concrete surface
h_{env} relative humidity of the surrounding environment
r_{CSH} reaction rate of CSH with carbon dioxide
$r_{p,ref}$ reference size of peak radius
r_p size of peak radius in different degrees of carbonation

they must withstand carbon dioxide pollution with a concentration five to six times higher than that in most other on-shore environments. A similar concern may be made for structures in modern cities at those latitudes where de-icing salts are heavily used in winter, and where the concentration of carbon dioxide is high because of pollution and traffic. Given the interaction of carbonation with the durability threat caused by the chloride ions ingress, both factors must be taken into account in the development of a simulation tool.

Carbonation influences the transport of chloride ions in concrete significantly. Numerous experiments have been carried out to study this influence [22–31]. According to those experimental researches, the precise influence of carbonation is so complicated that it is difficult to note whether carbonation will accelerate or decelerate the durability damage due to chloride ions. The influence of carbonation on the diffusion coefficient of chloride ions depends on the types and mix proportions of concretes considered experimentally [22,29–31].

An interesting phenomenon was reported in a new type of test where carbonation and chloride ingress were loaded alternately [24–26]. In that alternating test, the concentration of chloride ions was maximum near to the front of carbonation. Although carbonation and chloride ingress take place simultaneously, it should be noted that the diffusion of chloride ions is much faster than the rate of carbonation. That is, before carbonation, concrete usually contains Friedel's salt due to the chloride ion bound inside of concrete. Once the Friedel's salt reacts with carbon dioxide during the carbonation process, chloride ions are released to the pore solution in concrete as shown in the following equation.

$$3CaO\cdot Al_2O_3\cdot CaCl_2\cdot 10H_2O + 3CO_2 \rightarrow 3CaCO_3 + 2Al(OH)_3 + CaCl_2 + 7H_2O \quad (1)$$