



Probabilistic analysis of reinforcement corrosion due to the combined action of carbonation and chloride ingress in concrete



Xingji Zhu, Goangseup Zi*, Wonwoo Lee, Soye Kim, Jungsik Kong

School of Civil, Environmental & Architectural Engineering, Korea University, 5 Ga 1, An-Am Dong, Sung-Buk Gu, Seoul 136-701, Republic of Korea

HIGHLIGHTS

- A probabilistic model for the corrosion initiation of the steel reinforcement under the combined action of carbonation and chloride ingress is developed.
- The transport of carbon dioxide, chloride ions, heat and moisture are coupled in this probabilistic model.
- The key parameters for this probabilistic model are selected by using the one-way sensitivity analysis to minimize the computational cost.
- The probability of corrosion initiation in this combined action is much higher than that which would be obtained by considering the chloride penetration only.
- The time at corrosion initiation approximately follows a log-normal distribution in this combined action.

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ABSTRACT

This paper presents a comprehensive probabilistic model for the corrosion initiation of steel reinforcement due to the combined action of carbonation and chloride ingress in reinforced concrete structures. The coupled mechanism of the transport of carbon dioxide, chloride ions, heat and moisture is taken into account in this model. A minimum number of random variables were chosen from a sensitivity analysis to reduce the computational cost. The corrosion is assumed to be initiated when either the concentration of the free chloride ion exceeds its threshold value or the pH of the pore solution decreases to below 11. According to this model, the probability of the corrosion initiation in the above-mentioned combined action of carbonation and chloride ingress is almost two times higher than the case in which the two mechanisms are considered separately. The Kolmogorov-Smirnov test indicates that the time of corrosion initiation approximately follows a log-normal distribution in this combined action.

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1. Introduction

The corrosion of steel reinforcement is one of the most critical problems as it decreases the load-carrying capacity of reinforced concrete structures. The volume expansion of the corrosion products results in the cracking of the concrete cover which accelerates the migration of harmful ions into the concrete structures [1–3]. In addition, the nominal strength of the reinforcement is decreased by the corrosion [1,4]. Since an analysis of the entire deterioration caused by corrosion includes complicated physico-chemical mechanisms, the durability of reinforced concrete structures is often assessed by the corrosion initiation rather than by analyzing the detailed corrosion process to calculate the loss of the load-carrying capacity. Once the steel reinforcement completes the depassivation process, the generation of corrosion products and the swelling failure of the concrete cover occur soon after [5–7].

The corrosion initiation of the reinforcement would be triggered if either the content of the free chloride ions exceeds a certain threshold content, or the pH value decreases to a threshold value due to the carbonation [1,4,8–12]. In many cases, chloride ion ingress and carbonation occur at the same time. For example, the entrance of a cross-harbor tunnel needs to withstand a condition of salt spray and a high concentration of carbon dioxide. A similar case can be found in structures in modern cities where carbon dioxide pollution is severe due to excessive traffic and the heavy use of de-icing salts during winter weather.

Even in a normal environment, the influence of carbonation is noticeable. Some data indicate that the depth of carbonation on a concrete structure can be in the range of 10–20 mm after only 20 years service [1,4]. The thickness of the concrete cover of typical reinforced concrete structures is about 30–40 mm. The influence of carbonation on the transport of chloride ions is so significant that the two mechanisms need to be considered simultaneously [13–20]. A comprehensive deterministic model for this combined

* Corresponding author.

E-mail address: g-zi@korea.ac.kr (G. Zi).

durability problem was developed recently by the first and second authors [21].

Although the reliability of corrosion initiation has been studied by many authors, the ingress of chloride ions and the carbonation were considered independently from each other. For simplicity, the ingress of chloride ions has been modeled as a simple diffusion process. The binding capacity of chloride ions, convection, temperature, and humidity which significantly influence the transport of chloride ions are not considered in most of the works [22–30] except in [31]. While the probabilistic version of the corrosion initiation due to carbonation can be found in the literature [32–37]. However, these studies were based on the empirical prediction of the depth of carbonation to predict the pH near the steel reinforcement.

We present a probabilistic version of our deterministic model in this paper taking into account the uncertainty involved in this combined problem. The uncertainty considered in this paper can be classified into four different categories: (1) the uncertainty of the chloride threshold concentration which depends on the test methods [1,22]; (2) variability of external environmental conditions; (3) randomness of some properties of concrete, such as, the reduction of chloride binding capacity due to carbonation, the content of calcium oxide in concrete, the diffusion coefficients of chloride ions and carbon dioxide; and (4) variability of the concrete cover which depends on the quality of workmanship and control during the construction [22].

In the following section, Section 2, an overview of the combined mechanism of the ingress of chloride ions and the carbonation is given. The method of the probabilistic analysis and the calculation procedure are given in Section 3. We will then discuss the results in Section 4 using an illustrative example. The conclusion of this work is given in Section 5.

2. Combined action of carbonation and chloride ingress

2.1. Process of carbonation

The following aspects can be considered in the analysis of carbonation: transport of carbon dioxide, mass balance of dissolved calcium hydroxide, dissolution of solid calcium hydroxide into concrete pore solution and reaction of carbon dioxide with CSH ($3CaO \cdot 2SiO_2 \cdot 3H_2O$). These processes can be expressed by the following governing equations [21]

$$\frac{\partial(\phi - \phi_{w_e})C_{CO_2}}{\partial t} + \nabla \cdot \mathbf{J}_{CO_2} = -I_{ch} - I_{CSH} \quad (1)$$

$$\frac{\partial\phi_{w_e}C_{ch,d}}{\partial t} + \nabla \cdot \mathbf{J}_{ch,d} = -I_{ch} + I_d \quad (2)$$

$$\frac{\partial C_{ch,s}}{\partial t} = -I_d \quad (3)$$

$$\frac{\partial C_{CSH}}{\partial t} = -r_{CSH} \quad (4)$$

where C_{CO_2} is the molar concentration of carbon dioxide in the gas phase of pore (mol/m^3 of pore air), ϕ is the current porosity of the concrete, ϕ_{w_e} is the volume fraction of evaporable pore water (m^3 solution/ m^3 concrete), \mathbf{J}_{CO_2} is the flux of carbon dioxide, I_{ch} and I_{CSH} are the rates of the carbon dioxide consumption due to the reactions with $\text{Ca}(\text{OH})_2$ and CSH, respectively, $C_{ch,d}$ is the concentration of the dissolved calcium hydroxide (mol/m^3 of solution), $\mathbf{J}_{ch,d}$ is the flux of hydroxide ions generated by the dissolution of calcium hydroxide, I_d is the dissolved rate of the solid calcium hydroxide in the pore water, $C_{ch,s}$ is the molar concentration of solid calcium hydroxide (mol/m^3 of concrete), C_{CSH} is the molar concentration of CSH in concrete (mol/m^3 of concrete), and r_{CSH} is the reaction rate

of CSH with carbon dioxide. The calculation of diffusion coefficient for the carbon dioxide, the pH value and the degree of carbonation are summarized in Appendix A.

2.2. Influence of carbonation on chloride-induced corrosion

We assume that the transport of the chloride ions after carbonation still satisfies Fick's second law. The total amount of chloride in a unit volume of concrete is equal to the sum of the free chloride in the pore solution and the bound chloride in the form of Friedel's salt. Note that the bound chloride can be released to the pore solution by changing the binding capacity. Then, the governing equation can be given by [21]

$$\frac{\partial\phi_{w_e}C_{fc}}{\partial t} + \nabla \cdot \mathbf{J}_{fc} = I_{rc} \quad (5)$$

$$\mathbf{J}_{fc} = -\frac{1}{1 + \frac{1}{\phi_{w_e}} \frac{\partial C_{bc}}{\partial C_{fc}}} (D_{fc}^{car} \nabla \phi_{w_e} C_{fc} + \phi_{w_e} C_{fc} D_h^{car} \nabla h) \quad (6)$$

$$I_{rc} = \frac{d\alpha_L \phi_{w_e} C_{fc} (I_{ch} + I_{CSH})}{(1 + \frac{1}{\phi_{w_e}} \frac{\partial C_{bc}}{\partial C_{fc}}) [1 + \beta_L \phi_{w_e} (C_{fc}/b)] [C_{CaO}]_0} \quad (7)$$

where C_{fc} is the concentration of free chloride ions (kg/m^3 of pore solution), \mathbf{J}_{fc} is the flux of free chloride ions, I_{rc} is the source term reflecting free chloride ions released from Friedel's salt due to carbonation, C_{bc} is the content of bound chloride (kg/m^3 of concrete), D_{fc}^{car} and D_h^{car} are the diffusion coefficients of free chloride ions and moisture in the carbonated concrete, respectively, where their values depend on the degree of carbonation, d is the reduction factor of the binding capacity of chloride ions due to carbonation, α_L and β_L are parameters for the Langmuir isotherm depending on the type of concrete [21,38,39], $[C_{CaO}]_0$ is the initial molar concentration of the total calcium oxide in concrete, and b is the binder content per unit volume of concrete. Here, b is introduced because of the unit problem. The effect of carbonation on the diffusion coefficients D_{fc}^{car} and D_h^{car} is given in Appendix B.

Note that the ratio of the content of free chloride ions to the content of hydroxide ions is constant at the critical state of corrosion initiation [11,21]. Because the content of hydroxide ions will change during the carbonation process as shown in Eq. (2), the influence of carbonation on the threshold chloride value should also be considered. Here, we introduce a parameter η to reflect this influence. Then, the threshold value of chloride content considering the influence of carbonation can be given by

$$C_{th}^{car} = \eta C_{fc,th} \quad (8)$$

$$\eta = \frac{C_{ch,d}}{[C_{ch,d}]_0} \quad (9)$$

where η is a coefficient for the reduction of threshold chloride content due to carbonation, which is proposed based on the description in the literature [1,4,21], $C_{fc,th}$ is the threshold chloride content of non-carbonated concrete (% vs. binder weight), and $[C_{ch,d}]_0$ is the initial molar concentration of the dissolved calcium hydroxide (mol/m^3 of concrete). Note that $C_{ch,d}$ depends on the degree of carbonation as mentioned in Section 2.1.

In our mathematical model, we consider that chloride ingress does not influence the threshold pH value in this combined action.

3. Probabilistic analysis

3.1. Limit state of corrosion initiation

In the combined action of carbonation and chloride ingress, the initiation of corrosion depends on whether (1) the concentration of

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