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Improved numerical model for steel reinforcement corrosion in concrete considering influences of temperature and relative humidity

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HIGHLIGHTS

- An improved numerical model for steel reinforcement corrosion in concrete was developed.
- Influences of temperature and relative humidity on process control and corrosion rate were investigated.
- Effects of forward and reverse electrode reactions on activation overpotential were considered.
- Influence of temperature on the critical relative humidity under different conditions was discussed.

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ABSTRACT

An improved numerical model for steel reinforcement corrosion in concrete was developed to investigate the influences of temperature and relative humidity on process control and corrosion rate of steel reinforcement in concrete. In order to overcome the limitations of current numerical corrosion models which oversimplify the activation overpotential, the influences of both forward and reverse electrode reactions on the activation overpotential were considered based on the original formulation of the Butler-Volmer equation. Meanwhile, the influences of temperature and relative humidity on the kinetic parameters of corrosion and the properties of concrete pore solution were considered simultaneously. Moreover, the applicability and efficiency of the proposed numerical model for steel reinforcement corrosion were verified by comparing with current empirical prediction models as well as available experimental data of both artificially accelerated and natural exposure corrosion tests. Finally, the influences of temperature and relative humidity on process control and corrosion rate of steel reinforcement in concrete were investigated comprehensively. Furthermore, the influences of temperature, water-to-cement ratio, concrete cover depth, and chloride content on the critical relative humidity were also discussed.

1. Introduction

Corrosion of steel reinforcement in concrete has long been recognized as one of the major causes for durability deterioration of existing reinforced concrete (RC) structures [1–4]. It has been observed from experimental analysis that both temperature [5–7] and relative humidity [8,9] have significant effects on steel reinforcement corrosion in concrete. Hence, it is necessary to predict the corrosion rate of steel reinforcement in concrete under different environmental conditions (e.g., temperature and relative humidity) for service-life assessment and decision-making regarding the maintenance existing RC structures [10].

Based on the regression analysis of experimental data, various empirical prediction models [11–15] have been developed to establish the approximate relationships between corrosion rate of steel reinforcement and environmental or material parameters. According to the experimental data (2927 measurements) of 44 simulated bridge deck slabs over a 5-year exposure period, Liu and Weyers [11] proposed an empirical prediction model for corrosion rate in terms of concrete chloride content, temperature, Ohmic resistance of concrete cover, and corrosion time. It is obvious that this model ignores the influence of oxygen diffusion and concrete cover depth on corrosion rate of steel reinforcement. Vu and Stewart [12] developed an empirical prediction model of corrosion rate as the function of water-to-cement ratio, concrete cover depth, and corrosion time for a particular environmental condition with temperature of 20 °C and relative humidity of 75%. It should be noted that this model is based on the assumption that oxygen

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availability at the steel surface is the governing factor for steel reinforcement corrosion. As a result, it may not be applicable to corrosion processes where concrete resistivity is the governing factor. Ahmad and Bhattacharjee [13] proposed an empirical model to describe the relationship between the corrosion rate of steel reinforcement and material parameters such as water-to-cement ratio, cement content and chloride content. It is obvious that this model ignores the influences of environmental conditions (e.g., temperature and relative humidity) on corrosion rate of steel reinforcement. Furthermore, Scott and Alexander [14] proposed an empirical prediction model for corrosion rate of steel reinforcement by taking into account the influences of binder type, thickness of concrete cover and crack width, based on the experimental data of cracked concrete prismatic specimens. Otieno et al. [15] proposed an empirical prediction model for corrosion rate of cracked reinforced concrete structures in the marine tidal zone considering the influences of crack width, concrete cover depth, binder type and water-to-cement ratio. It is obvious that the above two models do not take into account the influences of environmental conditions such as temperature and relative humidity on corrosion rate of steel reinforcement explicitly. It is acknowledged that empirical prediction models are usually simple and straightforward to implement, but they cannot be adopted to explore the influencing mechanism of temperature and relative humidity on the process control and corrosion rate of steel reinforcement explicitly, since they don't take into account the processes and mechanisms of steel reinforcement corrosion [16–18].

In recent years, several numerical models have been developed to investigate the influence of temperature and relative humidity on steel reinforcement corrosion in concrete. Isgor et al. [19] developed a numerical model for steel reinforcement corrosion by taking into account the influence of relative humidity on the cathodic limiting current density (in terms of effective oxygen diffusion coefficient) and the influence of temperature on the Tafel slopes. However, it neglects the influence of temperature on the kinetic parameters of reinforcement corrosion as well as the effects of temperature and relative humidity on the properties of concrete pore solution (e.g., electrical resistivity of concrete). Yu et al. [20] investigated the influence of relative humidity on the process control of reinforcement corrosion in concrete based on a numerical model for steel reinforcement corrosion, which takes into account the influences of temperature and relative humidity on the electrical resistivity of concrete as well as the influence of relative humidity on the cathodic limiting current density. But it neglects the influence of temperature on the kinetic parameters of reinforcement corrosion in concrete. Pour-Ghaz et al. [21] investigated the influence of temperature on corrosion rate based on a numerical model for steel reinforcement corrosion, by taking into account the influences of temperature on both kinetic parameters of steel reinforcement corrosion and the properties of concrete pore solution. However, the influence of relative humidity on the process control and corrosion rate of steel reinforcement in concrete was neglected. In theoretical analysis, it is necessary to take into account the influence of temperature on the kinetic parameters of reinforcement corrosion (e.g., exchange current density, Tafel slope, and equilibrium potential) [21] as well as the influences of temperature and relative humidity on the properties of concrete pore solution (e.g., electrical resistivity of concrete and limiting current density) [22]. However, as described above, current numerical models for steel reinforcement corrosion [19–21] cannot take into account the influences of temperature and relative humidity comprehensively. Furthermore, current numerical models for steel reinforcement corrosion [19–21,23–25] usually ignore the influence of reverse electrode reaction on the activation overpotential based on the assumption that the rate of the forward reaction of the electrode is significantly greater than the reverse reaction. Nevertheless, investigation shows that the activation overpotential calculated based on the above assumption would be far from the real one, when the ratio of net current density to exchange current density of the electrode is small. As a result, the process control and corrosion rate predicted by the simplified corrosion models may not always be accurate. Hence, it is desirable to develop an improved numerical model for steel reinforcement corrosion which can be adopted to investigate the influences of temperature and relative humidity on the process control and corrosion rate of steel reinforcement in concrete more rationally.

The main objective of this study is to develop an improved numerical model for steel reinforcement corrosion and to investigate the influences of temperature and relative humidity on the process control and corrosion rate of steel reinforcement in concrete. Firstly, an improved numerical model for steel reinforcement corrosion was developed by taking into account the influences of both forward and reverse electrode reactions on the activation overpotential as well as the influences of temperature and relative humidity on the kinetic parameters of corrosion and the properties of concrete pore solution. Then the applicability and efficiency of the proposed model were verified by comparing with the current empirical prediction models as well as available experimental data of both artificially accelerated and natural exposure corrosion tests. Finally, the influences of temperature and relative humidity on the process control and corrosion rate of steel reinforcement in concrete were investigated comprehensively.

2. Improved numerical model for steel reinforcement corrosion in concrete

2.1. Governing equation and boundary conditions of numerical corrosion model

Steel reinforcement in concrete is generally well protected against corrosion by a passive film that is quite stable in the high alkaline environment provided by concrete. However, penetration of aggressive agents such as chloride ions through concrete cover and/or carbonation of concrete cover may result in the destruction of passive film (depassivation) and the initiation of active corrosion. In general, the areas on which the depassivation of steel reinforcement in concrete occurs are called as "anode", while on which the passivation of steel reinforcement in concrete occurs are called as "cathode", as shown in Fig. 1a. If the water and oxygen are adequate near the steel/concrete interface, the corrosion of steel reinforcement will start. In order to establish the numerical model of steel corrosion in concrete, a typical zone with cover depth of d and length of L at the underside of reinforced concrete member is considered for simplicity. The lengths of anode and cathode are expressed as L_a and L_c respectively, as shown in Fig. 1b. If the assumption of electrical charge conservation and isotropic conductivity is adopted, the governing equation for distribution of corrosion potential within concrete cover can be described as [20]

$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} = 0 \qquad (1)$$

where, E is corrosion potential (V); x and y are planar coordinates (m).

In order to solve the Eq. (1) based on the numerical methods (such as finite difference method or finite element method), the boundary conditions of corrosion model should be defined. As shown in Fig. 1b, the boundary conditions on the interface between steel reinforcement and concrete are required to meet the anodic and cathodic corrosion potentials, while the other boundary conditions are defined as $\partial E/\partial n = 0$, where n indicates direction. According to the principle of corrosion electrochemistry, the anodic and