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Prediction model for the time-varying corrosion rate of rebar based on micro-environment in concrete

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HIGHLIGHTS

- ▶ Corrosion rate of rebar is controlled by activation polarizations under atmosphere.
- ▶ Electrochemical fundamental model for corrosion rate of rebar in concrete is built.
- ▶ Prediction model for the time-varying corrosion rate of rebar in concrete is built.

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ABSTRACT

The corrosion rate of rebar in concrete is time dependent, and calculation of this rate is very important in predicting corrosion cracking and the corresponding service life of the rebar. In the present paper, the controlling factors of the corrosion rate of rebar in concrete under atmospheric environment were first analyzed, and conclusion for joint control of cathode and anode activation polarizations was drawn. Based on the corrosion dynamic equations under activation polarization control, an electrochemical fundamental model for the corrosion rate of rebar was established. Then, based on this model and the test results on the corrosion of rebar in concrete and the resistivity of concrete under artificial climate environment, a prediction model for the corrosion rate of rebar was presented comprehensively, which takes into account the effects of the concrete's micro-environment and corrosion time. Finally, feasibility of the prediction model was verified through comparisons between the predicted and measured values both under artificial and natural climate environment.

1. Introduction

One of the main concerns in the durability assessment and service-life prediction of reinforced concrete structures is the prediction of the corrosion rate of rebar in concrete. Theoretical analysis and experimental research on the corrosion rate of rebar have been carried out by many domestic and foreign scholars, and some positive results were obtained. Lopez and Gonzalez [1] and Enevoldsen et al. [2] analyzed the influence of pore water saturation, resistivity, and internal relative humidity of concrete on the corrosion rate of rebar and suggested that a critical pore water saturation or relative humidity initiates corrosion of rebar. Song and Liu [3] and Liang et al. [4] studied the corrosion of rebar in carbonized concrete and established a prediction model for the corrosion rate. Liu and Weyers [5] developed a prediction model for the time-varying corrosion rate of rebar, which considered the influence of chloride-ion concentration, temperature, and resistance of concrete based on long-term exposure test under natural climate environment. Ji et al. [6] analyzed the controlling factors of the corrosion of rebar under atmospheric environment and established a corrosion rate model, which considered the time-varying effect and the influence of environmental temperature and humidity based on the principle of electrochemical corrosion. Yuan et al. [7,8] studied the time-varying process mechanism of the corrosion rate of rebar in concrete and proposed a development mode of corrosion rate for the entire lifetime of the rebar.

At present, the time variation of the corrosion rate of rebar in concrete and the influence of climate conditions are given increasing attention. However, establishment of a prediction model for the corrosion rate of rebar is still deficient of a theoretical basis, and the controlling factors of corrosion rate lacks correct and accordant understanding. The corrosion rate time-varying process for the entire lifetime of the rebar has not also been considered, which causes inaccuracy in the application of the prediction model for corrosion rate. Further, the factors that directly affect the corrosion of rebar in concrete, namely, temperature and moisture content in the concrete's micro-environment, are not clearly expressed in existing models.

In the current paper, the factors that control the corrosion rate of rebar in concrete were first analyzed, and an electrochemical

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fundamental model for corrosion rate was established based on the corrosion dynamic equation under activation polarization control. Then, based on the established model and the test results on the corrosion rate of rebar and the resistivity of concrete under artificial climate environment, a prediction model for the time-varying corrosion rate of rebar was presented, which considered the effects of the concrete's micro-environment. Finally, the feasibility of the prediction model was verified through comparisons between the predicted and tested values of the corrosion rate of rebar in concrete under artificial and natural climate environment conditions. The action spectra of the climate environment and the corresponding response spectra of the concrete's micro-environment can be directly applied in the prediction of corrosion rate based on the research results.

2. Electrochemical fundamental model of corrosion rate of rebar in concrete

2.1. Analysis of the controlling factors of corrosion rate

Corrosion of rebar in concrete is an electrochemical reaction process, which includes the oxidation reaction in the anode and the reduction reaction in the cathode. In the corrosion process, the electrode potential deviation from the equilibrium potential when electric current flows through the electrode is called as electrode polarization. Electrode polarization and the opposite depolarization occur simultaneously. The electrode reaction process of the corrosion of rebar consists of a series of different steps in which the slowest step that determines the speed of the entire electrode reaction process is called the control step. Electrode polarization can be divided into concentration polarization, electrochemical polarization (or activation polarization), and resistance polarization, based on the control steps. On the other hand, electrochemical corrosion can be divided into anode-control, cathode-control, mixed-control, and resistance-control types, according to the degree of polarization of the cathode and the anode.

Liu and Weyers [5] showed that the oxygen content at the surface of the rebar exceeds the needed oxygen amount for steel corrosion in concrete under normal outdoor exposure environment, and steel corrosion is controlled by oxygen diffusion and slows down only when the concrete structure is completely immersed in water. Ji et al. [6] indicated that the corrosion process of the rebar in concrete in normal atmospheric environment is jointly controlled by the cathode and anode reactions and not exclusively by the cathode reaction. Huet et al. [9] suggested that the control type of the cathode reaction of steel corrosion in concrete depends on pore water saturation (S) of concrete. The cathode reaction process is controlled by concentration polarization (oxygen diffusion) when $0.9 \leqslant S \leqslant 1$, by activation and concentration polarizations when $0.8 \leqslant S < 0.9$, and by activation polarization when $S < 0.8$.

Based on the foregoing analysis, conclusion can be made that the corrosion of rebar in a concrete structure is not controlled by oxygen diffusion in the natural atmosphere environment because the requirement for steel corrosion can be met by the oxygen content in the concrete pore. The cathode reaction for steel corrosion has no difficulty obtaining oxygen supply even if the concrete cover is saturated by rain because rainwater is usually saturated with dissolved oxygen. Moreover, some corrosion products will replace oxygen as new depolarization agent in the cathode process during the formation of corrosion products, i.e., high-valence iron ions in the rust at the rebar surface are reduced [10].

$$8FeOOH + Fe^{2+} + 2e^- \rightarrow 3Fe_3O_4 + 4H_2O \tag{1}$$

$$Fe^{3+} + e \rightarrow Fe^{2+} \tag{2}$$

$$Fe_3O_4 + H_2O + 2e \rightarrow 3FeO + 2OH^- \tag{3}$$

$$Fe(OH)_3 + e \rightarrow Fe(OH)_2 + OH^- \tag{4}$$

Therefore, the cathode reaction of the steel corrosion in concrete was determined to be controlled by activation polarization under atmospheric environment. In the current study, the controlling factor for the corrosion rate of rebar was determined to be the combined action of the cathode and anode activation polarizations.

2.2. Corrosion dynamic equations

After the factor controlling the corrosion rate of rebar in concrete has been determined, a theoretical model for corrosion rate can be built using the corrosion dynamic equations under the activation polarization control of the metal corrosion theory. The specific corrosion dynamic equations are the following [11]:

$$\text{Anode reaction}: \ i_a = \vec{i}_a - \overleftarrow{i}_a = i_{0,a}\left[\exp\left(\frac{\alpha_a n_a F}{RT}\eta_a\right) - \exp\left(-\frac{\alpha_c n_a F}{RT}\eta_a\right)\right] \tag{5a}$$

$$\text{Cathode reaction}: \ i_c = \overleftarrow{i}_c - \vec{i}_c = i_{0,c}\left[\exp\left(\frac{\alpha_c n_c F}{RT}\eta_c\right) - \exp\left(-\frac{\alpha_a n_c F}{RT}\eta_c\right)\right] \tag{5b}$$

where i_a is the corrosion current density of the micro-cell anode in the activation region of the rebar (μA/cm^2), i_c is the corrosion current density of the micro-cell cathode in the activation region of the rebar (μA/cm^2) and $i_{0,a}$ is the exchange current density of the anode reaction in the activation region of the rebar (μA/cm^2) expressed as

$$i_{0,a} = n_a F K_a c_R \exp\left(\frac{\alpha_a n_a F E_{e,a}}{RT}\right) = n_a F K_a c_R \exp\left(\frac{-9500}{T}\right) \tag{6a}$$

where $i_{0,c}$ is the exchange current density of the cathode reaction in the activation region of the rebar (μA/cm^2) expressed as

$$i_{0,c} = n_c F K_c c_O \exp\left(\frac{\alpha_c n_c F E_{e,c}}{RT}\right) = n_c F K_c c_O \exp\left(\frac{2612}{T}\right) \tag{6b}$$

where α_a and α_c are the electronic transfer coefficients in the anode and the cathode of the corrosion system, respectively; $\alpha_a + \alpha_c = 1$, n_a is the number of electrons gained or lost in the anode reaction of micro-cell; $n_a = 2$, n_c is the number of electrons gained or lost in the cathode reaction of micro-cell; $n_c = 1$, F is the Faraday constant; $F = 96{,}500$ C/mol, R is the gas constant; $R = 8.314$ J/(mol K), T is the absolute temperature (K), η_c and η_a are the overpotential of the cathode and anode polarization, respectively (V).

2.3. Fundamental model for the corrosion rate of rebar

According to the basic equations of metal corrosion dynamics under activation polarization control, an electrochemical fundamental model for the corrosion rate of rebar in concrete has been established according to the charge conservation in metal corrosion system. The basic assumptions for building the model are hereby presented. (1) The cathode and anode reactions in the corrosion micro-cell both occur in the activation region of the rebar. (2) The corrosion of rebar in concrete is in accordance with the mixed potential theory, i.e., the corrosion potential is jointly determined by the cathode and anode processes that happen synchronously. (3) $\alpha_a = \alpha_c = 0.5$.

For most of the corrosion system, according to the electrochemical principle, the corrosion potential (E_{cor}) is far from the