

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.

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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.

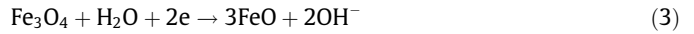
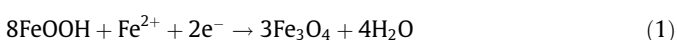
2. Electrochemical fundamental model of corrosion rate of rebar in concrete

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 $0.9 \leq S \leq 1$, by activation and concentration polarizations when $0.8 \leq S < 0.9$, 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].



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]:

$$\begin{aligned} \text{Anode reaction: } i_a &= \bar{i}_a - \bar{i}_a \\ &= i_{0,a} \left[\exp\left(\frac{\alpha_a n_a F}{RT} \eta_a\right) - \exp\left(-\frac{\alpha_c n_c F}{RT} \eta_a\right) \right] \end{aligned} \quad (5a)$$

$$\begin{aligned} \text{Cathode reaction: } i_c &= \bar{i}_c - \bar{i}_c \\ &= i_{0,c} \left[\exp\left(\frac{\alpha_c n_c F}{RT} \eta_c\right) - \exp\left(-\frac{\alpha_a n_a F}{RT} \eta_c\right) \right] \end{aligned} \quad (5b)$$

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

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

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

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

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; $F = 96,500 \text{ C/mol}$, R is the gas constant; $R = 8.314 \text{ J/(mol K)}$, 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

equilibrium potential ($E_{e,a}$) of the metal and ($E_{e,c}$) of the depolarization agent in the activation region. Thus, under corrosion potential (E_{cor}), i_a is much less than $i_{a,0}$, and i_c is much less than $i_{c,0}$, as shown in Fig. 1.

Therefore, the second terms of Eqs. (5a) and (5b) can be ignored, and Eqs. (5a) and (5b) can then be simplified as

$$i_a = i_{0,a} \exp\left(\frac{\eta_a}{\beta_a}\right) = i_{0,a} \exp\left(\frac{E_{cor} - E_{e,a}}{\beta_a}\right) \quad (7a)$$

$$i_c = i_{0,c} \exp\left(\frac{\eta_c}{\beta_c}\right) = i_{0,c} \exp\left(\frac{E_{e,c} - E_{cor}}{\beta_c}\right) \quad (7b)$$

where E_{cor} is the spontaneous corrosion potential in the activation region of the rebar; (V) and $E_{e,a}$ is the equilibrium potential of the anodic dissolution reaction (V), obtained from the Nernst equation

$$\begin{aligned} E_{e,a} &= E_{Fe^{2+}/Fe}^0 + \frac{2.3RT}{n_a F} \lg[Fe^{2+}] \\ &= -0.44 + \frac{2.3 \times 8.314T}{2 \times 96,500} \lg(1.65 \times 10^{-13}) \\ &= -0.44 \\ &\quad - 0.00127T \quad [\text{standard hydrogen electrode (SHE)}] \end{aligned} \quad (8a)$$

where $E_{e,c}$ is the equilibrium potential of the cathode reduction reaction (V), also obtained from the Nernst equation

$$\begin{aligned} E_{e,c} &= E_{O_2/OH^-}^0 + \frac{2.3RT}{n_c F} \lg \frac{[O_2][H_2O]^2}{[OH^-]^4} \\ &= 0.401 + \frac{2.3 \times 8.314T}{4 \times 96500} \lg \frac{0.21}{(10^{-1})^4} \\ &= 0.401 + 1.6458 \times 10^{-4} T \quad (\text{SHE}) \end{aligned} \quad (8b)$$

where β_c and β_a are the natural logarithm Tafel slopes of the polarization curve in the cathode and the anode of the corrosion micro-cell of rebar, respectively, expressed as

$$\beta_a = \frac{RT}{\alpha_a n_a F} \quad (9a)$$

$$\beta_c = \frac{RT}{\alpha_c n_c F} \quad (9b)$$

If the exchange current density of the cathode and anode reactions are $i_{0,c}^0$ and $i_{0,a}^0$, respectively, when the temperature is 25 °C (considering $i_{0,c}^0 = 1 \times 10^{-3} \mu\text{A}/\text{cm}^2$ and $i_{0,a}^0 = 3 \times 10^{-2} \mu\text{A}/\text{cm}^2$ in reference to literature [12]), for any temperature T

$$i_{0,a} = i_{0,a}^0 \exp\left[9500\left(\frac{1}{298} - \frac{1}{T}\right)\right] \quad (10a)$$

$$i_{0,c} = i_{0,c}^0 \exp\left[2612\left(\frac{1}{T} - \frac{1}{298}\right)\right]. \quad (10b)$$

Eqs. (9) and (10) show that the temperature has a great influence on $i_{0,a}$ and $i_{0,c}$ but little influence on β_a and β_c .

According to the electrochemical basic principle, the cathodic current is equal to the anodic current; subsequently,

$$I_{cor} = i_a \times A_{ha} = i_c \times A_{hc} \quad (11)$$

where I_{cor} is the current strength (A) of the micro-cell corrosion in the activation region of the rebar, A_{ha} is the anode area (cm^2) of the micro-cell in the activation region of the rebar, and A_{hc} is the cathode area (cm^2) of the micro-cell in the activation region of the rebar.

Eqs. (6a), (6b), and (11) are combined and solved; thus

$$I_{cor} = (i_{0,a} A_{ha})^{\frac{\beta_a}{\beta_a + \beta_c}} (i_{0,c} A_{hc})^{\frac{\beta_c}{\beta_a + \beta_c}} \exp\left(\frac{E_{e,c} - E_{e,a}}{\beta_a + \beta_c}\right). \quad (12)$$

The concept of activation ratio (δ), the ratio of the activation area (A_h) to the total surface area (A_i) of the rebar in concrete, is introduced in the present paper; then

$$A_h = \delta \cdot A_i. \quad (13)$$

For the micro-cell corrosion, the anode and the cathode areas are equal in the entire activation region due to the tiny sizes and unfixed positions of the cathode and the anode [13,14]; thus

$$A_{ha} = A_{hc} = \frac{1}{2} A_h = \frac{1}{2} \delta \cdot A_i. \quad (14)$$

Substituting Eq. (14) into Eq. (12) yields the following equation:

$$i_{cor} = \frac{1}{2} \delta (i_{0,a})^{\frac{\beta_a}{\beta_a + \beta_c}} (i_{0,c})^{\frac{\beta_c}{\beta_a + \beta_c}} \exp\left(\frac{E_{e,c} - E_{e,a}}{\beta_a + \beta_c}\right) \quad (15)$$

where i_{cor} is the average corrosion current density corresponding to the surface area ($\mu\text{A}/\text{cm}^2$) of the rebar in concrete.

Eq. (15) is the electrochemical fundamental model for the corrosion rate of rebar in concrete. To determine the corrosion rate of rebar, the Tafel slopes (β_a and β_c) of the electrode polarizations must be determined. According to the metal corrosion principle, electrode polarization reflects the imbalance between the reaction rate of electrode and the migration rate of particles. The development of corrosion layer around the steel surface and the resistance of concrete affect the electrode polarization and influence β_a and β_c . In the current work, the prediction model for the time-varying corrosion rate of rebar in concrete can be finally established by determining the prediction model of the Tafel slopes β_a and β_c .

3. Prediction model for the time-varying corrosion rate of rebar

The prediction model for the time-varying corrosion rate of rebar in concrete is established in accordance with the electrochemical fundamental model combined with the development mode of the corrosion rate for the entire lifetime of rebar in concrete under artificial climate conditions. This model is aimed mainly at the time-varying stages before the corrosion cracking of rebar in concrete contaminated with chloride under atmospheric environment and includes the influence of the concrete's micro-environment on the corrosion rate.

3.1. Basic expression of the model

Of all the factors that affect the corrosion rate of the rebar, the temperature of concrete exerts little influence on the Tafel slopes but greatly influences the exchange current densities of the cathode and anode reactions. The pore water saturation of concrete affects the resistivity of concrete and its corrosion resistance—the

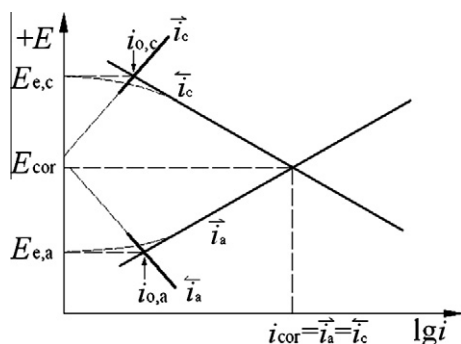


Fig. 1. Semi-log corrosion polarization figure: (a) $W/C = 0.62$, (b) $W/C = 0.54$ and (c) $W/C = 0.48$.

Tafel slopes of the cathode and anode reactions. In addition, the Tafel slopes vary with corrosion time of the rebar.

Consequently, based on the electrochemical fundamental model [Eq. (15)], the corrosion rate model of the rebar that considers the effects of temperature, resistivity of concrete, and corrosion time can be expressed as

$$i_{cor} = \frac{1}{2} \delta (i_{0,a})^\lambda \cdot (i_{0,c})^{1-\lambda} \cdot \exp \left[\frac{\Delta E_e}{\beta_a(\tau, \rho_{con}) + \beta_c(\tau, \rho_{con})} \right] \quad (16)$$

in which

$$\lambda = \frac{\beta_a(\tau, \rho_{con})}{\beta_a(\tau, \rho_{con}) + \beta_c(\tau, \rho_{con})}$$

$$i_{0,a} = 3 \times 10^{-2} \exp \left[9500 \left(\frac{1}{298} - \frac{1}{T} \right) \right]$$

$$i_{0,c} = 1 \times 10^{-3} \exp \left[2612 \left(\frac{1}{T} - \frac{1}{298} \right) \right]$$

$$\Delta E_e = E_{e,c} - E_{e,a} = 525 + 1.44T$$

where T is the absolute temperature (K) at the depth of the rebar in concrete, τ is the corrosion time (days), ρ_{con} is the resistivity of concrete (Ωm), and ΔE_e is the initial difference in equilibrium potential (mV) in the corrosion of rebar.

Moreover, from the test results of accelerated corrosion specimens in the literature [7], the control degree of the anode reaction to the corrosion of rebar is basically equal to that of the cathode reaction, i.e., $\beta_a/(\beta_a + \beta_c) = \beta_c/(\beta_a + \beta_c) \approx 0.5$. Therefore, Eq. (16) can be further simplified into

$$i_{cor} = \frac{1}{2} \delta (i_{0,a})^{0.5} (i_{0,c})^{0.5} \exp[\Delta E_e/\beta(\tau, \rho_{con})] \quad (17)$$

where β is the sum of the Tafel slopes in the cathode and anode of steel corrosion and the function of corrosion time and concrete's resistivity.

3.2. Calculation model of Tafel slope β

During the accelerated corrosion process, the Tafel slopes were recorded when the corrosion rate of the rebar in concrete was measured, and part of the results are shown in Fig. 2. The Tafel slopes changed with time during the corrosion of rebar in concrete; the time-varying process of slope β is opposite to that of the corrosion rate of rebar because slope β indicates the level of corrosion resistance.

From the time-varying mode of the corrosion rate of rebar in its entire lifetime [7], the time-varying mode of the Tafel slope can be obtained, as shown in Fig. 3, where β_0, β_1 , and β_2 are the characteristic values of the Tafel slope during the time-varying process.

According to the time-varying mode of the Tafel slope, the calculation model of slope β proposed in the present study corresponding to development stages TP-2 and TP-3 of the corrosion rate of rebar can be expressed as

$$\begin{cases} \beta_1 = f(W/C, \rho_{con}) & \tau = \tau_1 \\ \beta = \beta_1 + \gamma \cdot \tau; \quad \gamma = f(W/C, \rho_{con}) & \tau_1 \leq \tau < \tau_2 \\ \beta = \beta_2 = \beta_1 + \gamma \cdot \tau_2 & \tau_2 \leq \tau < \tau_3 \end{cases} \quad (18)$$

Based on the analysis of the measurement data of steel corrosion in concrete with different water–cement ratio and chloride content, the calculation model for Tafel slope β corresponding to time-varying stage TP-2 of the corrosion rate is finally obtained, expressed as

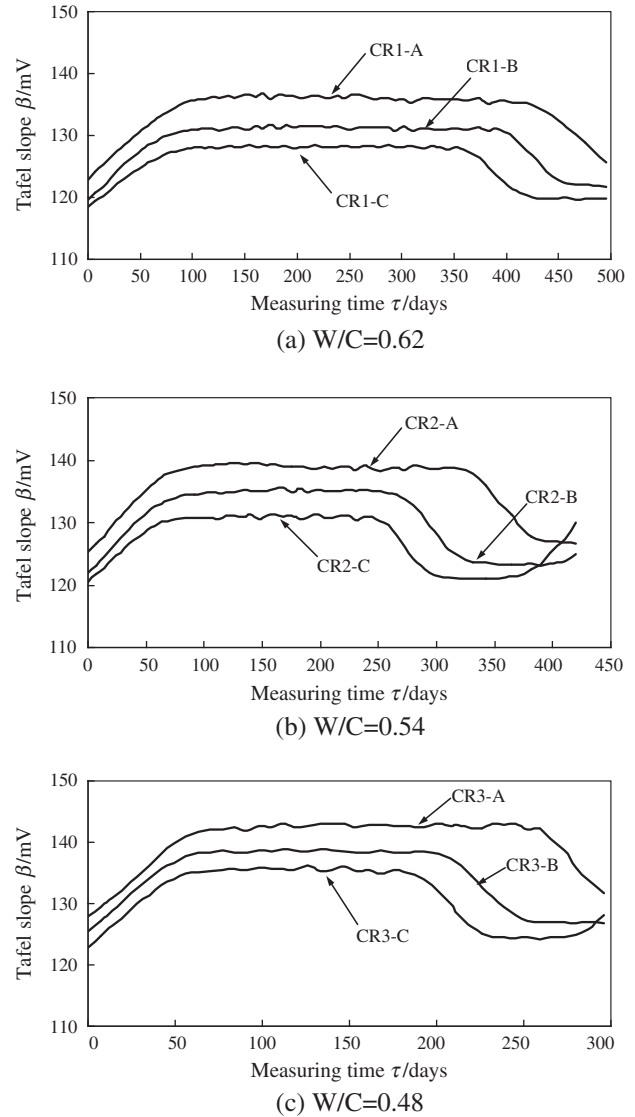


Fig. 2. Changes in the Tafel slopes of corrosion of rebar with time.

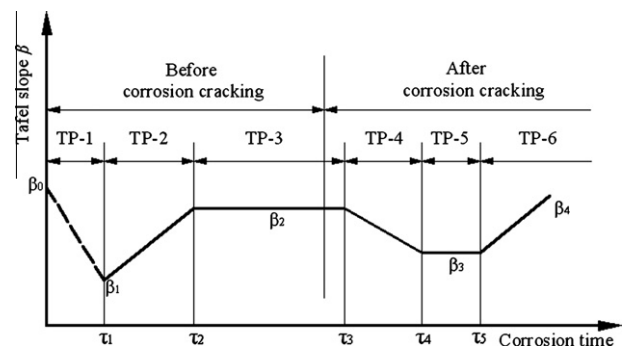


Fig. 3. Stages of the time-varying process of Tafel slope: (a) $W/C = 0.62, Cl = 2.427\%$, (b) $W/C = 0.54, Cl = 3.641\%$ and (c) $W/C = 0.48, Cl = 4.855\%$.

$$\begin{cases} \beta_1 = 143.78 - 54 \times (W/C) + 0.018 \rho_{con} & \tau = \tau_1 \\ \beta = \beta_1 + [0.78 - 0.92 \times (W/C) - 1.2 \times 10^{-4} \rho_{con}] \cdot \tau & \tau_1 \leq \tau < \tau_2 \end{cases} \quad (19)$$

where W/C is the water–cement ratio, and its applicable range is 0.48–0.62.

Simultaneously, Eq. (18) shows that time point τ_2 must be determined to obtain Tafel slope β_2 corresponding to time-varying stage TP-3 of the corrosion rate. Time-varying stage TP-2 is considered as the free-expansion phase of the corrosion products in the present study. The calculation formula of the corrosion quantity per unit area of rebar during the free-expansion phase is

$$\Delta M_{pf} = 0.0302 \times (W/C) - 0.0111 \quad (20)$$

According to Faraday's law, the relationship among corrosion quantity, corrosion current density (i_{cor}), and corrosion time is as follows:

$$\Delta M = \frac{N \times A_i \times \int i_{cor} \times \tau}{F} \quad (21)$$

where N is the gram equivalent of steel ($N = M/n$; $n = 2$) and τ is the corrosion time (days).

Thus, the relationship between time point τ_2 and the corrosion quantity per unit area of rebar during the free-expansion phase is

$$\frac{N \times \int_0^{\tau_2} i_{cor} d\tau}{F} = 0.0302 \times (W/C) - 0.0111 \quad (22)$$

3.3. Prediction model for the time-varying corrosion rate of rebar considering the effects of micro-environment in concrete

From the basic expression of the time-varying model of corrosion rate of rebar and the calculation model of the Tafel slope, the prediction model for corrosion rate of rebar that considers the influence of temperature, resistivity of concrete, and corrosion time is finally established. According to the time-varying characteristic of the corrosion rate of rebar in concrete under natural climate environment, the prediction model involves only the descending phase of TP-2 and the steady phase of TP-3 before corrosion cracking. The specific expressions of the model are as follows:

$$i_{cor} = \frac{1}{2} \delta (i_{0,a})^{0.5} (i_{0,c})^{0.5} \exp[\Delta E_e / \beta(\tau, \rho_{con})] \quad (23)$$

in which

$$i_{0,a} = 3 \times 10^{-2} \exp \left[9500 \left(\frac{1}{298} - \frac{1}{T} \right) \right]$$

$$i_{0,c} = 1 \times 10^{-3} \exp \left[2612 \left(\frac{1}{T} - \frac{1}{298} \right) \right]$$

$$\Delta E_e = E_{e,c} - E_{e,a} = 525 + 1.44T$$

$$\beta(\tau, \rho_{con}) = \begin{cases} \beta_1 = 143.78 - 54 \times (W/C) + 0.018\rho_{con} & \tau = \tau_1 \\ \beta_1 + [0.78 - 0.92 \times (W/C) - 1.2 \times 10^{-4}\rho_{con}] \cdot \tau & \tau_1 \leq \tau < \tau_2 \\ \beta_1 + [0.78 - 0.92 \times (W/C) - 1.2 \times 10^{-4}\rho_{con}] \cdot \tau_2 & \tau_2 \leq \tau \leq \tau_3 \end{cases}$$

$$\frac{N \times \int_0^{\tau_2} i_{cor} d\tau}{F} = 0.0302 \times (W/C) - 0.0111$$

Eq. (23) shows that the resistivity of concrete must first be determined to predict the corrosion rate of rebar in concrete. The resistivity of concrete is affected by many factors, so the calculation model should be established through experimental research to determine the resistivity of concrete under different conditions. The influencing factors considered in the test included water–cement ratio, chloride-ion content, and pore water saturation of concrete. The concrete resistance of specimen was measured using traditional electrotechnology method, and the resistivity of concrete was subsequently calculated. Some test results on the resistivity of concrete under different conditions are shown in Fig. 4.

Based on the test results of the resistivity of concrete in combination with the analysis of the influence of temperature on the concrete resistivity in the literature [15], the calculation model for the resistivity of concrete considering the effects of water–cement ratio, chloride-ion content, temperature, and pore water saturation is expressed as

$$\rho_{con} = [750,605 \times (W/C) - 106,228] \times \exp \left[-0.4417 \times Cl - 7.7213 \times S + 2889 \left(\frac{1}{T} - \frac{1}{303} \right) \right] \quad (24)$$

where W/C is the water–cement ratio, Cl is the total chloride-ion content (%) in concrete (the quality percentage of cement), and S is the pore water saturation of concrete near the surface of the reinforced bar and is calculated from the concrete internal temperature and relative humidity. T is the absolute temperature (K) of concrete ($T = 273 + t$, where t is the temperature expressed in degree Celsius).

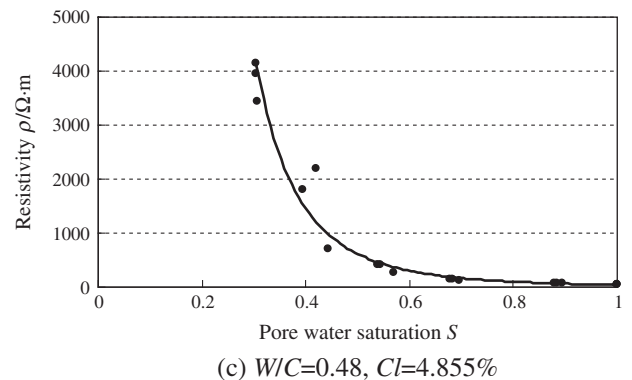
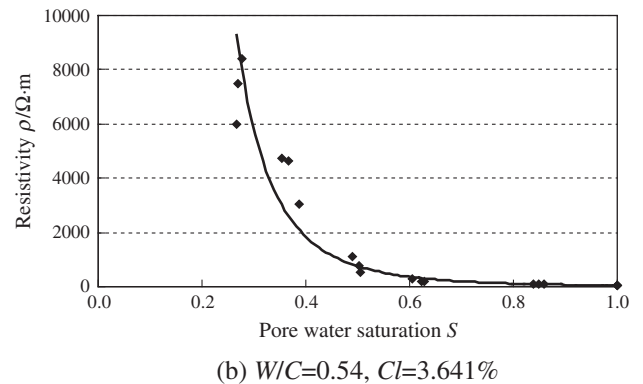
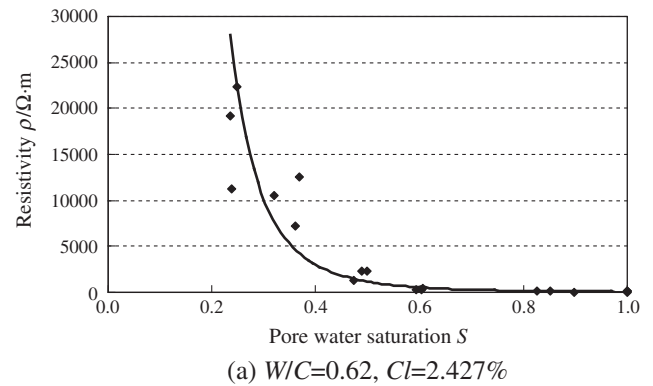


Fig. 4. Changes of the resistivity with the pore water saturation of concrete.

4. Test verification for predicting the corrosion rate of rebar

4.1. Test under artificial climate environment

To verify the applicability of the prediction model for the corrosion rate of rebar, the theoretical values of the corrosion rate are calculated using Eq. (23) and compared with the corresponding measured values based on the test results of steel corrosion under artificial climate conditions.

4.1.1. Test on corrosion rate of rebar in concrete

The test results of corrosion rate of steel bars in the literature [16] were used to verify the application of the model under artificial climate conditions.

In the test, the water–cement ratio (W/C) of the specimen concrete was 0.55, and the compressive strength of concrete was 25.4 MPa at 28 days. The reinforced concrete specimens underwent accelerated corrosion under artificial climate environment; the environmental temperature was $(30 \pm 2)^\circ\text{C}$, and the relative humidity was $(85 \pm 5)\%$. At the same time, the sodium chloride that accounted for 5% quality of the cement was mixed into the concrete to accelerate the corrosion of rebar. The corrosion rate (corrosion current density) of rebar in concrete was measured periodically. The measurement results of corrosion rate are shown in Fig. 5.

4.1.2. Comparison between measured and calculated values of corrosion rate

First, the theoretical values of the corrosion rate of rebar in concrete were calculated using Eq. (23) under the test conditions.

4.1.2.1. Known parameters.

- The water–cement ratio is 0.55, the thickness of the concrete cover is 15 mm, and the diameter of the rebar is 14 mm.
- The actual temperature of concrete is approximately 28°C , and the relative humidity in concrete is approximately 85%.
- The chloride mixture content is 5% of the quality of the cement in concrete; converting this gives the total content of chloride ion (Cl) as 3.034% of the quality of cement.

4.1.2.2. Calculation process.

- According to the internal temperature and relative humidity in concrete, the calculated pore water saturation is 0.680. The calculation of the pore water saturation will be described in detail in another paper.
- The water–cement ratio is 0.55, the total chloride-ion content is 3.034%, and the pore water saturation is 0.680; thus, the resistivity of concrete can be calculated using Eq. (24).

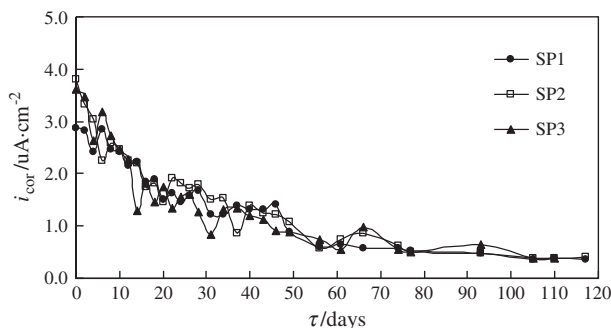


Fig. 5. Changes of the corrosion rate of steel bars.

$$\begin{aligned} \rho_{\text{con}} &= [750,605 \times (W/C) - 106,228] \\ &\times \exp\left[-0.4417 \times Cl - 7.7213 \times S + 2889\left(\frac{1}{T} - \frac{1}{303}\right)\right] \\ &= (750,605 \times 0.55 - 106,228) \times \exp[-0.4417 \times 3.034 \\ &- 7.7213 \times 0.680 + 2889 \times (1/301 - 1/303)] = 448.57 \Omega \text{ m}. \end{aligned}$$

(c) As sodium chloride is mixed into the concrete to accelerate the corrosion of rebar, the starting time of the corrosion rate measurement can be approximately considered as the characteristics of time τ_1 in the time-varying process of the Tafel slope; the corresponding characteristic value of the Tafel slope is

$$\begin{aligned} \beta_1 &= 143.78 - 54 \times (W/C) + 0.018\rho_{\text{con}} \\ &= 143.78 - 54 \times 0.55 + 0.018 \times 448.57 = 122.15 \text{ mV}. \end{aligned}$$

When

$$\begin{aligned} \tau_1 \leq \tau < \tau_2, \beta &= \beta_1 + [0.78 - 0.92 \times (W/C) - 1.2 \times 10^{-4} \rho_{\text{con}}] \cdot \tau \\ &= 122.15 + [0.78 - 0.92 \times 0.55 - 1.2 \times 10^{-4} \times 448.57] \cdot \tau \\ &= 122.15 + 0.220\tau \text{ mV}. \end{aligned}$$

(d) The exchange current densities of the cathode and anode are calculated when the temperature is 28°C .

$$i_{0,a} = 3 \times 10^{-2} \exp\left[9500\left(\frac{1}{298} - \frac{1}{301}\right)\right] = 4.12 \times 10^{-2} \mu\text{A}/\text{cm}^2$$

$$i_{0,c} = 1 \times 10^{-3} \exp\left[2612\left(\frac{1}{301} - \frac{1}{298}\right)\right] = 9.16 \times 10^{-4} \mu\text{A}/\text{cm}^2$$

(e) The equilibrium potential difference between the cathode and the anode is calculated as

$$\Delta E_e = 525 + 1.44 \times (273 + 28) = 958.44 \text{ mV}.$$

(f) Substituting the calculated results of above-mentioned parameters into Eq. (23) yields the following model:

$$i_{\text{cor}} = \frac{1}{4} \times (0.0412)^{0.5} \times (0.000916)^{0.5} \exp(958.44/\beta(\tau)).$$

Consequently, $\beta(\tau = 14) = 125.23 \text{ mV}$ when the corrosion rate is measured for the first time, which is introduced into the above formula; the result is

$$i_{\text{cor}}(0) = 3.24 \mu\text{A}/\text{cm}^2.$$

The corresponding measured values of the corrosion rate of rebar in the three specimens are 3.80, 3.39, and 2.88 $\mu\text{A}/\text{cm}^2$, respectively. When $0 < \tau \leq \tau_2$, the corrosion current density of the rebar is

$$i_{\text{cor}}(\tau) = \frac{1}{4} \times (0.0412)^{0.5} \times (0.000916)^{0.5} \exp\left(\frac{958.44}{122.15 + 0.220\tau}\right).$$

Then, time point τ_2 is determined according to Eq. (22), i.e.,

$$\frac{28 \times \int_0^{\tau_2} i_{\text{cor}}(\tau) d\tau}{1.117} = 0.0302 \times 0.55 - 0.0111.$$

Therefore, $\tau_2 = 152 > 120$ days.

The comparisons between the calculated and measured values of the corrosion rate of rebar are shown in Fig. 6. The calculated

values of the corrosion current density of the rebar from Eq. (23) basically agree with the measured values under artificial climate environment. In addition, the standard error between the average values of the prediction and measurement is 0.66, verifying the soundness of the calculation results from Eq. (23).

4.2. Test under natural climate environment

To verify the applicability of the prediction model for the time-varying corrosion rate of rebar under natural environment, tests on the corrosion rate of rebar were conducted under sheltered conditions in the natural climate environment. The influence of the random fluctuations of climate environmental conditions must be considered in predicting the corrosion rate of rebar under natural climate environment.

4.2.1. Experimental research on the corrosion rate of rebar

The concrete grade of the used specimens was C25, and its water–cement ratio was 0.54; the diameter of the HRB335 steel bar was 14 mm; and the thickness of concrete cover was 25 mm. A portion of the measurement results of the corrosion rate of rebar in concrete is shown in Fig. 7.

4.2.2. Comparison between measured and calculated values of corrosion rate

The theoretical values of the corrosion rate of rebar in concrete under natural climate environment were calculated using Eq. (23). The main ideas are as follows: first, the action spectra of the climate environment were built based on the meteorological data in the natural environment. Then, the response spectra of the concrete’s micro-environment were built based on the action spectra of the climate environment. Finally, the corrosion rate of rebar in concrete was calculated based on the response spectra of the concrete’s micro-environment. The specific calculation process was the same as that under artificial climate environment.

The action spectra of the climate environment and the response spectra of the concrete’s micro-environment used in the prediction of corrosion rate of rebar were quoted from the literature [17,18]. The comparison between the predicted and measured values of the corrosion rate of rebar in concrete under sheltered conditions in natural climate environment is shown in Fig. 8.

Fig. 8 shows that the theoretical values of the corrosion rate of rebar calculated using Eq. (23) are basically consistent with the measured values, and the standard error between the two is only 0.310 because the influence of the concrete’s micro-environment on the corrosion rate has been considered in the prediction model. The prediction model for the corrosion rate presented in the current study is verified as also applicable to the corrosion of rebar in concrete under natural climate conditions.

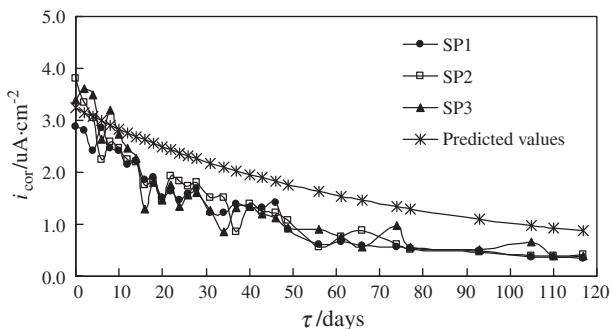


Fig. 6. Comparisons between calculated and measured values of corrosion rate of steel bars under artificial climate.

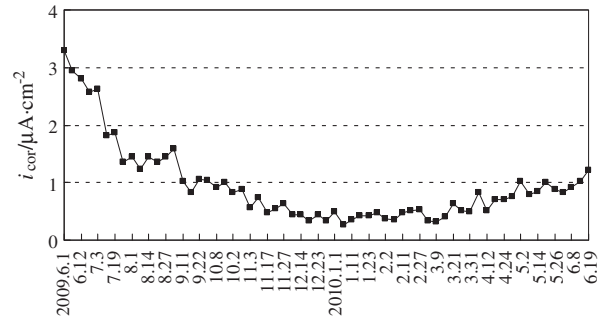


Fig. 7. Measuring results of corrosion rate of steel bar in concrete under shelter conditions [5.26 stands for May 26, 2010 in the abscissa].

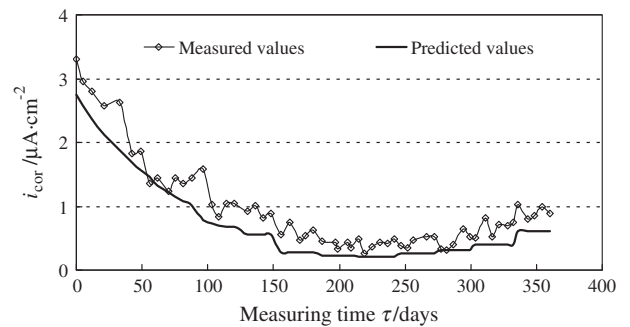


Fig. 8. Comparisons between calculated and measured values of steel corrosion rate in concrete under natural climate environment.

5. Conclusions

- (1) The corrosion rate of rebar in concrete is jointly controlled by the cathode and anode activation polarizations under atmospheric environment because the oxygen content in concrete pore is sufficient, and some corrosion products will replace oxygen as the new depolarization agent in the cathode process during the formation of corrosion products on the steel surface.
- (2) From the basic equations of metal corrosion dynamics under activation polarization control, the electrochemical fundamental model for the corrosion rate of rebar in concrete is developed according to the charge conservation in the corrosion system. The model reflects the relationship between the corrosion current density of the rebar and the internal factors in the corrosion system.
- (3) Based on the electrochemical fundamental model and the development mode of corrosion rate in the entire lifetime of the rebar in concrete under artificial climate conditions, the prediction model for the time-varying corrosion rate of rebar in concrete is established, which considers the effects of concrete’s micro-environment. The feasibility of the model is fully proven by the comparisons between the predicted and the measured values of the corrosion rate of rebar in concrete under artificial and natural climate environment.

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