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Practical model for predicting corrosion rate of steel reinforcement in concrete structures

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HIGHLIGHTS

- A practical prediction model for steel corrosion rate in concrete was developed.
- Influential parameters on control mode and steel corrosion rate were investigated.
- Potential differences between surface and steel/concrete interface were presented.
- Influences of cover depth on corrosion initiation and propagation were discussed.

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ABSTRACT

A practical model for predicting the corrosion rate of steel reinforcement in concrete structures was proposed. The numerical model with nonlinear boundary conditions for the macrocell corrosion of steel reinforcement in concrete structures was established based on the electrochemical principles and the Bulter–Volmer equation. The influences of various parameters such as anode-to-cathode (A/C) ratio, relative humidity, concrete resistivity, cover thickness on the corrosion control mode and corrosion rate of steel reinforcement in concrete structures were then investigated. Finally, a practical model for predicting the corrosion rate of steel reinforcement in concrete structures was proposed based on a comprehensive nonlinear regression analysis with easily quantifiable engineering parameters, such as water-to-cement (W/C) ratio, chloride content, thickness of concrete cover and relative humidity. Model comparison and experimental verification demonstrate that the proposed prediction model is of good accuracy and applicability to real life scenarios in terms of capturing the corrosion behavior of steel reinforcement in different situations.

1. Introduction

Deterioration of reinforced concrete (RC) structures due to the carbonation or chloride ingress induced corrosion of steel reinforcement is a major concern for infrastructure owners and operators [1]. The service life of the RC structures with respect to the corrosion of steel reinforcement is usually divided into two distinct phases – the corrosion initiation and the corrosion propagation [2]. The former refers to the depassivation of steel reinforcement induced by the ingress and accumulation of aggressive agents such as the chloride ions and carbon dioxide, while the latter starts from corrosion of steel reinforcement to structural failure induced by the cracking/spalling of concrete cover or steel bar strength degradation. The corrosion rate of steel reinforcement not only determines the speed of formation and accumulation for corrosion products which influences the performance of concrete cover and the serviceability of RC structures, but also controls the reduction rate of effective cross-section area of steel bar and the load-bearing capacity of RC structures. Hence, the corrosion rate of steel reinforcement plays an important role in safety evaluation, maintenance decision and residual life prediction of the existing RC structures.

Over the past several decades, the corrosion of steel reinforcement in concrete structures has been widely investigated and various prediction models including the empirical models, reaction control models (oxygen diffusion or concrete resistivity) and electrochemical models for the corrosion rate of steel reinforcement have been proposed [3].

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The empirical models are generally based on the assumed direct relationships between the corrosion rate and basic structural parameters (e.g. water-to-cement (W/C) ratio, binder type, thickness of concrete cover, et al.) and environmental parameters (e.g. temperature, relative humidity, chloride concentration, et al.). The unknown coefficients of the empirical models are usually determined by referring to the relevant experimental data. Liu and Weyers [4] proposed a nonlinear regression model for the corrosion rate as a function of the chloride content, temperature, ohmic resistance of concrete cover, and active corrosion time, based on the measured corrosion parameters of forty four bridge deck slabs over a five-year outdoor exposing period. It is clear that this model ignores the influence of oxygen and adopts ohmic resistance of concrete cover as a governing parameter which causes the prediction model to be geometry dependent. Scott and Alexander [5] discussed the influences of the binder type, thickness of concrete cover and crack width on the corrosion rate of steel reinforcement in the cracked concrete prismatic specimens, based on seven concrete mixtures comprising ordinary Portland cement (OPC) and blends of the OPC with different supplementary cementitious materials. Jiang et al. [6] carried out an accelerated corrosion experiment on reinforced concrete specimens in a computer-controlled chamber and fitted a prediction model of the corrosion rate by taking the temperature, relative humidity, thickness of concrete cover, W/C ratio into account. Yu et al. [7] investigated the influences of the W/C ratio, thickness of concrete cover, chloride content, mineral admixtures on corrosion rate, but the influence of the relative humidity was ignored. Zhu and Xie [8] proposed an empirical model to describe the relationship between the corrosion rate and concrete resistance as well as corrosion potential, based on the corrosion parameters detected by the linear polarization device Gecor 6. However, it fails to consider the influence of the oxygen and is also geometry dependent. Although the empirical model is simple and convenient for engineers, it is often limited to the set of conditions under which they are developed. Since selected variables under consideration are investigated in isolation from other influencing parameters and/or the interaction thereof [2].

The reaction control models assume that the electrical resistivity (ion transportation) and oxygen diffusion resistance (cathodic reaction) of concrete cover are two major controlling factors for the corrosion of steel reinforcement in concrete structures. They indirectly take into account other influencing factors such as the temperature, relative humidity, W/C ratio and binder type, et al. Vu and Stewart [9] assumed that corrosion of steel reinforcement in concrete structures was limited by the availability of oxygen at the steel surface and established a prediction model of corrosion rate as a function of the W/C ratio and cover thickness when the relative humidity is 75% and the temperature is 20 °C. Although the influence of the oxygen supply is reflected in the prediction model, it neglects the concrete electrical resistivity and therefore is only suitable for corrosion of steel reinforcement under the control of cathodic reaction. Based on the assumption that the concrete was water saturated and the corrosion of steel reinforcement was under the control of oxygen diffusion, Huet et al. [10] established a prediction model for corrosion rate as a function of the porosity, oxygen concentration, degree of water saturation, and oxygen diffusion coefficient in concrete pore liquid. Furthermore, Alonso et al. [11] established an empirical relationship between the corrosion rate and concrete electrical resistivity by fitting the experimental data. Although the reaction control models consider the influence of the oxygen diffusion (cathodic reaction) or concrete resistivity (ion transportation) on corrosion rate, their unknown coefficients are generally determined by fitting the experimental data and they belong to quasi-empirical models in nature.

The electrochemical models are based on the electrochemical principles of corrosion and establish the prediction model of corrosion rate with the electrochemical parameters. Stern [12] found a linear dependence of the potential on logarithmic scales of applied current for small amounts of polarization in the experiment. Consequently they proposed the linear polarization theory which determines the corrosion rate when the anodic/cathodic Tafel slope and the polarization resistance were known. Using the equivalent circuit approach set up for a well-defined two-dimensional geometry, Raupach and Gulikers [13] calculated the corrosion rate with the anodic/cathodic polarization resistance, concrete resistance, and anodic/cathodic equilibrium potential. Isgor and Razaqpur [14] built a macrocell corrosion model for steel reinforcement in concrete structures by considering both the anodic/cathodic activation polarization and the cathodic diffusion polarization. Li et al. [15] established a modified macrocell corrosion model by considering the impact of rebar stress on corrosion rate. Cao et al. [16] built a prediction model which could consider both the macrocell and microcell corrosion simultaneously, based on the examination of the anodic/cathodic activation polarization and the cathodic diffusion polarization. Yu et al. [17] investigated the influences of the cover thickness, concrete resistivity and degree of pore saturation of concrete on the corrosion mechanism and corrosion rate of steel reinforcement in concrete structures based on the macrocell corrosion model. Generally, the electrochemical models are rigorously established and could comprehensively reflect corrosion mechanism if the electrochemical parameters are selected rightly. However, the electrochemical models are often computationally time-consuming and too complex to be adopted by the general engineering community.

Although a large number of prediction models for the corrosion rate of steel reinforcement in concrete structures have already been developed, lots of challenges remain such as the determination of electrochemical parameters, numerical difficulties in solution of governing equations due to nonlinear boundary conditions and complicacies in modeling complicated geometries (e.g. reinforcement details) and non-homogeneous material properties, et al. Therefore, a practical model of sufficient accuracy and easy application in terms of predicting the corrosion rate of steel reinforcement in concrete structures is desirable. The main objective of this study is to develop a practical model for predicting the corrosion rate of steel reinforcement in concrete structures with easily quantifiable engineering parameters. The influences of important engineering parameters, such as the anode-to-cathode (A/C) ratio, relative humidity, concrete resistivity, thickness of concrete cover, et al., on the corrosion control mode and corrosion rate of steel reinforcement were investigated first based on the numerical model of macrocell corrosion. Then a practical model for predicting corrosion rate of steel reinforcement in concrete structures was proposed based on a comprehensive nonlinear regression analysis with easily quantifiable engineering parameters, such as the W/C ratio, chloride content, thickness of concrete cover and relative humidity. Finally, both model comparison and experimental validation to demonstrate the accuracy and practicality of the proposed prediction model were performed.

2. Macrocell corrosion model of steel reinforcement in concrete

2.1. Corrosion mechanism of steel reinforcement in concrete

Corrosion of steel reinforcement in concrete structures is a complicated electrochemical process. As newly cast concrete is highly alkaline, a passive film can form on the steel surface, which will prevent the initiation of corrosion of steel reinforcement. However, the passive film gradually dissolves with the ingress and accumulation of the carbon dioxide or chloride ions within concrete cover, which will generate a potential difference between the active and