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The effect of temperature on the corrosion of steel in concrete. Part 2: Model verification and parametric study

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ABSTRACT

A comprehensive model for predicting the corrosion rate of steel in concrete has been developed using the concept of simulated polarization resistance experiments. This model is developed by carrying out a nonlinear regression analysis on data obtained from numerical experiments that are based on the solution of Laplace's equation in a domain determined by the polarized length of the rebar. This part of the paper provides a comprehensive verification of the developed model and illustrates the application of the model to investigate the coupled effects of parameters affecting corrosion of steel in concrete. The results of the verification study show that the model predictions are in good agreement with the experimental data.

1. Introduction

The authors of this paper have investigated the effect of temperature on the corrosion rate of steel corrosion in concrete using simulated polarization resistance experiments [1]. The simulated experiments were based on the numerical solution of the Laplace's equation with predefined boundary conditions of the problem and have been designed to establish independent correlations among corrosion rate, temperature, kinetic parameters, concrete resistivity and limiting current density for a wide range of possible anode/cathode (A/C) distributions on the reinforcement. The results, which successfully capture the resistance and diffusion control mechanisms of corrosion as well as the effect of temperature on the kinetic parameters and concrete/pore solution properties, have been used to develop a closed-form regression model for the prediction of the average and maximum corrosion rates of steel in concrete

$$\left\langle \begin{matrix} i_{\text{corr,ave}} \\ i_{\text{corr, max}} \end{matrix} \right\rangle = \frac{1}{\tau\rho^{\gamma}}\left(\eta T d^{\kappa} i_L^{\lambda} + \mu T v^{i_L^{\varpi}} + \theta(Ti_L)^{\vartheta} + \chi\rho^{\gamma} + \zeta\right) \quad (1)$$

where ρ (Ω m) is the concrete resistivity, T (K) is temperature, d (m) is concrete cover thickness and i_L (A/m^2) is the limiting current density. The coefficients of the equation (i.e., $\tau, \gamma, \eta, \kappa, \lambda, \mu, v, \varpi, \theta, \vartheta, \chi, \zeta$) are provided in Table 1.

The model for the average corrosion rate, which is comparable to the expected measurements of actual polarization resistance tests, were obtained from the regression analysis of the average current density data with associated variables (i.e., temperature, resistivity, limiting current density and cover thickness). The average current densities were calculated by dividing the calculated corrosion current at the optimum (or equilibrium) A/C ratio, at which current reaches its maximum value, over the anodic area of the rebar. The maximum corrosion rate, which can be considered as representative of the pitting corrosion rate for small A/C ratios, is the maximum calculated corrosion rate on the surface of steel. This maximum corrosion rate occurs at the transition point between anode and cathode where the maximum polarization of anode occurs.

In the present paper, the developed model will be verified with three experimental studies. The first verification is intended to illustrate the capability of the model in accurately capturing the effect of temperature. The second verification illustrates the ability of the model in capturing the effect of the degree of saturation, and finally, the third verification shows the capability of the model to capture the effect of concrete cover accurately. Furthermore, a parametric study is conducted on the corrosion rate of steel in concrete using the developed model in which the coupled effect of different parameters on the steel corrosion is considered. The parametric study illustrates the capability of the model to account for concrete properties such as w/c ratio.

2. Experimental verification of the model

In this section three experimental studies from the literature are compared with the developed model. A brief summary of the methods and materials used in each experiment are presented; further details of the experiments can be found in the corresponding original references.

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Table 1
The constants of the developed model given in Eq. (1).

$i_{corr,ave}$		$i_{corr,max}$	
Constant	Value	Constant	Value
τ	$1.181102362 \times 10^{-3}$	τ	1
η	$1.414736274 \times 10^{-5}$	η	0.32006292
ζ	−0.00121155206	ζ	−53.1228606
κ	0.0847693074	κ	0.00550263686
λ	0.130025167	λ	0.120663606
γ	0.800505851	γ	0.787449933
μ	$1.23199829 \times 10^{-11}$	μ	$-3.73825172 \times 10^{-7}$
θ	−0.000102886027	θ	47.2478753
ϑ	0.475258097	ϑ	0.00712334564
χ	$5.03368481 \times 10^{-7}$	χ	0.003482058
ν	90487	ν	784679.23
ϖ	0.0721605536	ϖ	0.0102616314

Table 2
Input data for the model used to compare the model with experiments conducted by Lopez et al. [2].

RH (%)	Temperature (K)	Limiting current density (A/m^2)	Resistivity (Ω m)
50	273	0.926	33179
90	273	0.02684	252
F.I.[a]	273	0.008	149
50	303	2.4	5356
90	303	0.070	68
F.I.	303	0.015	43
50	323	4.15	1908
90	323	0.12	32
F.I.	323	0.026	21

Cover thickness = 0.0065 m.
[a] Full immersion: for calculating the oxygen diffusion coefficient the relative humidity of F.I. is considered 99%.

2.1. Lopez et al. [2]

The first experimental work to verify the developed model is obtained from Lopez et al. [2]. This verification is chosen to illustrate the capability of the model in capturing the variation of corrosion rate with temperature. The general setup of the experiments conducted by Lopez et al. [2] is as follows: Two rebars of 10 mm diameter were embedded in mortar specimens of dimensions $2 \times 5.5 \times 8$ cm in symmetric positions along with a central stainless steel bar as working electrode. The mortars had 1:3:0.5 cement/sand/water ratio and contained 0%, 2%, 4% and 6% chloride content that was added in the form of NaCl by the weight of cement. After curing for 40 days in 100% relative humidity, specimens were exposed to three levels of temperature (0 °C, 30 °C, 50 °C), three levels of relative humidity (50%, 90% and full immersion) resulting in 36 cases. The corrosion rate of rebars was measured with the polarization resistance method.

The temperature and concrete cover thickness are provided in the original work [2], however, the concrete resistivity and the limiting current density needed to be estimated for each of the 36 cases. For estimating the concrete resistivity through the available data, the following procedure is implemented: assuming equilibrium conditions, the corresponding degree of saturation to the each relative humidity is calculated using the adsorption isotherm proposed by Xi et al. [3]. The required data of the isotherm (i.e., w/c ratio, the age of concrete and temperature) are provided in the original reference. Once the w/c ratio and the saturation of concrete are known, the resistivity of concrete at 20 °C is calculated using the experimental data obtained by GjØrv et al. [4] using Table A.1 provided in the appendix. The equations in Table A.1 were obtained through regression analyses of GjØrv's experimental data. The resistivity of the desired temperature, T, then is calculated using

$$\rho = \rho_o e^{\frac{\Delta U_\rho}{R}\left(\frac{1}{T}-\frac{1}{T_o}\right)} \tag{2}$$

where R (≈8.314 J/(mole K)) is the universal gas constant, ρ_o (Ω m) is the resistivity at the reference temperature, T_o (K), and ΔU_D (kJ/mole) is the activation energy of the Arrhenius relationship [5] given in Eq. (A.1) of the appendix.

The limiting current density is also estimated for each case using the following procedure: the amount of dissolved oxygen in water for each temperature is calculated using the Henry's law [6]. The oxygen diffusion coefficient of the concrete, D_{O_2} (m^2/s), is calculated using the model proposed by Papadakis et al. [7], which is also provided in Part 1 of this investigation [1]. Having determined these parameters, the limiting current density is calculated using

$$i_L = z_c F \frac{D_{O_2} C^s_{O_2}}{d} \tag{3}$$

where $C^s_{O_2}$ (mole/m^3) is the amount of dissolved oxygen on the surface of concrete, z_c is the number of electrons participating the cathodic reaction and F (≈96500 C/mole) is the Faraday's constant [1]. It should be noted that the effect of chloride content on concrete properties, such as resistivity, is not considered here. The input data used in this verification are presented in Table 2.

Fig. 1 compares the results of the experiments conducted by Lopez et al. [2] with the average and maximum corrosion current densities obtained using the model. The experimental data of the chloride contaminated samples for all values of relative humidity and temperature are very close to the average current density predictions and mostly between the average and maximum corrosion current densities predicted by the model. Experimental data related to samples with 0% chloride contamination, on the other hand, are overestimated by the model predictions. This is due to the fact that, in these samples the depassivation had not yet occurred (i.e., steel was not actively corroding), and the model presented in this work is only applicable to cases in which depassivation has already taken place; i.e., for active steel. Therefore this behaviour was expected.

The fact that the experimental data is closer to the average corrosion density predictions confirms accuracy of the model in predicting measurements of actual polarization resistance experiments, which are also averaged over the polarized area of the rebar. As it can be observed in Fig. 1, there is up to one order of magnitude difference between the values of average and maximum corrosion current density predictions of the model, which may appear wide. However, it should be noted that maximum corrosion rate predictions are mostly used to simulate possible pitting behaviour, which may not be accurately captured by actual polarization resistance tests. Experimental investigations of Gonzalez et al. [8] show that the pitting corrosion rate can be up to 8 times larger than the measured values with common polarization resistance instruments. These instruments may not capture pitting behaviour since they average the measuring current over the entire length of the reinforcement. The maximum corrosion current density suggested herein can be regarded as the upper limit of the corrosion rate, representing possible pitting behaviour; therefore it provides more information than common polarization resistance tests.

In addition, it should be noted that in Fig. 1 measurements from actual polarization resistance tests are widely scattered. For example, in Fig. 1a the corrosion rate of samples with 6% chloride contamination decreases with increase of temperature, and highest corrosion rate is seen at 0 °C. This can be explained as experimental noise since with decreasing temperature (1) the resistivity of concrete increases, (2) the diffusion coefficient of concrete decreases; therefore, it is expected that the corrosion rate would decrease. It has been reported in the literature that the polarization resistance