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THE INFLUENCE OF W/C RATIO, CONCRETE COVER THICKNESS AND DEGREE OF WATER SATURATION ON THE CORROSION RATE OF REINFORCING STEEL IN CONCRETE

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ABSTRACT

The mathematical model for the chloride-induced corrosion of reinforcing steel in concrete is applied to analysis of the influence of the concrete quality (w/c ratio), concrete cover thickness and the degree of water saturation on the corrosion current density. The governing equations of electrical potential and oxygen transport through concrete, as well as the boundary conditions for the polarisation on the cathodic part of steel surface are described. The numerical procedure based on the finite element and finite difference method is developed to solve the set of equations.

Introduction

Several theoretical models for the steel corrosion in concrete have been proposed [1-3]. It is clear from these models that the cathodic part of the corrosion cell has a strong influence in controlling the rate of corrosion. Oxygen is necessary for the cathodic process and the rate of oxygen diffusion through the concrete to the reinforcement determines rate of corrosion process.

However, there are some questions still to be answered. How this process is influenced by other possible controlling factors? The moisture content of the concrete also plays a notable role in determining the rate of corrosion of steel embedded in concrete. The water influences this process in at least two ways: a) the degree of water saturation appears to have a dominating influence on the electrical resistivity of concrete and b) the moisture content appears to have dominating effect on the mobility (diffusivity) of oxygen [4, 5].

In dry concrete the corrosion rate is too low and could not be considered as an influence of primary importance for the durability. Increasing the moisture content will have the effect of increasing the electrical conductivity, i.e. increasing corrosion current density. After exceeding a threshold value for water saturation, corrosion process becomes diffusion governed and the corrosion rate decreases.

The aim of this paper is to calculate, for various concrete qualities and concrete cover thicknesses, such a degree of water saturation at which the steel corrosion rate is highest.

The calculations are based on the model realized in the scope of space-and-time discretisation. In the analysis and caluclations presented in this paper the following assumptions are made:

(i) the concentration of chloride ions has reached the threshold value for active corrosion,
(ii) the degree of water saturation for the case under study is equal along the entire cross-section of the concrete sample,
(iii) in the range of water saturation which is to be considered in the model the corrosion process is subjected to mixed cathodic-ohmic control.

Model Description

The steel corrosion in concrete is an electrochemical process [1, 6-10] influenced by electrical resistivity of concrete and the steel surface, the alkalinity of the cement composite in contact with steel, the presence of electrolyte in the concrete and the concentration of oxygen dissolved in the pore liquid near the reinforcing steel.

Before formulating the governing equations it should be repeated shortly that the corrosion process can be considered in the form of an electrical circuit in which the electric current is defined by a potential between the anode and cathode [1]. In ref. [1] the electrode potential, $\Delta\Phi$, is expressed as the potential difference between the electrode and adjacent electrolyte, and is generally determined by Nernst equation

$$\Delta\Phi = \Delta\Phi_0 + \frac{RT}{nF}\, ln \left(\frac{Q_{\mathrm{oxid}}}{Q_{\mathrm{red}}} \right) \tag{1}$$

where T is the absolute temperature, R is the molar gas constant (8.315 J/ (K·mol)), F is the Faraday's constant (9.648×10^4 C/mol), n is equal to the number of electrons involved in the reaction at the electrode, Q_{oxid} and Q_{red} are oxidation and reduction rates at the electrode, while $\Delta\Phi_0$ is the standard electode potential (electrode potential if the concentration in the adjacent solution is 1 mol/dm^3, T_0 = 298.15 K, p_0 = 101325 Pa) and is measured with respect to the standard hydrogen electrode.

According to Bažant [1], the potential between the metal electrode and electrolyte next to the anode surface (in volts at 25°C) is expressed by means of the following relation

$$\Delta\Phi^A = \Phi^A_{st} - \Phi^A_{con} = -0.409 + 0.0296 \,\log\,(C_F/C^A_W) \tag{2}$$

while the relation for the potential between the metal electrode and the electrolyte next to the cathode is

$$\Delta\Phi^{C} = \Phi^{C}_{st} - \Phi^{C}_{con} = 0.512 + 0.0148 \log\left(C^{C}_{O}/C^{C}_{W}\right), \tag{3}$$

where C_F, C_W and C_O are concentrations of ferrous (II) hydroxide, capillary water and oxygen in concrete (per unit volume of concrete), Φ_{st} is the constant potential of reinforcing steel, Φ_{con} is the concrete (electrolyte) potential next to the electrode surface while superscripts *A* and *C* refer to anode and cathode, respectively.

Because of low ohmic resistance of a steel bar as compared to concrete, the electric potential difference between cathode and anode is negligible, hence $\Phi^{C}_{st} \approx \Phi^{A}_{st} = \Phi_{st}$. As the reinforcing steel potential is constant, the value $\Phi_{st} = 0$ was selected.

Governing equations. Assuming that the degree of water saturation is equal along the entire cross-section of concrete cover and that the concentration of chloride ions has reached the threshold for active corrosion, the equations governing the steel corrosion process are as follows:

$$\frac{\partial C_O}{\partial t} = D_O \nabla^2 C_O \tag{4}$$

$$CATHODE: \quad D_O \frac{\partial C_O}{\partial r} = k_3 \sigma \frac{\partial \Phi}{\partial r} \tag{5}$$

$$ANODE: \quad D_O \frac{\partial_O}{\partial r} = -k_4 \sigma \frac{\partial \Phi}{\partial r} \tag{6}$$

$$\nabla^2 \Phi = 0 \tag{7}$$

$$CATHODE: \quad \Phi = -0.512 - 0.0148 \log\left(C_O/C_W\right) \tag{8}$$

where D_O is the coefficient of oxygen diffusion through concrete, σ is the electric conductivity of concrete, while k_3 and k_4 are cathodic and anodic reaction constants. The equation (4) describes the oxygen transport, while equations (5) and (6) are boundary conditions for the cathodic and anodic part of the corrosion cell and represent Faraday's law. The equation (7) is the Laplace equation for electric potential, while the cathodic potential is determined by equation (8).

The initial and subsequent boundary conditions related to equations (4) and (7) are:

a) oxygen transport

$$C_O = C_O(r,z) \ for \ t = t_p, \ R_{st} \le r \le R_{st} + d_{con}, \ -L_C/2 \le z \ L_A/2$$

$$C_O = \epsilon C_O^{sea} \ for \ r = R_{st} + d_{con}, \ t > t_p$$

$$\frac{\partial C_O}{\partial z} = 0 \text{ for } z = L_A/2 \text{ and } z = -L_C/2,\ t > t_p$$

where L_C and L_A are cathode and anode lengths, respectively, R_{st} is the steel bar radius, d_{con} is the cover thickness of concrete, ϵ is the capillary porosity of concrete cover, while t_p is the time of depassivation.

b) Laplace equation

According to Bažant [1], the potential difference between the anode and electrolyte next to the anode surface is taken to be fixed, i.e. $\Delta\Phi^A = -0.712$ V. In other words, it is assumed that the anode is unpolarisable. Hence, the initial and subsequent boundary conditions are:

$$\Phi = 0 \text{ for } 0 \le t \le t_p,\ R_{st} \le r \le d_{con},\ -L_C/2 \le z \le L_A/2$$

$$\frac{\partial \Phi}{\partial r} = 0 \text{ for } r = R_{st} + d_{con},\ t > t_p$$

$$ANODE:\ \ \Phi = 0.712\ V \text{ for } r = R_{st},\ t > t_p$$

$$\frac{\partial \Phi}{\partial z} = 0 \text{ for } z = L_a/2 \text{ and } z = -L_C/2,\ t > t_p.$$

The boundary condition at the concrete surface in contact with air expresses the fact that no current can be transmitted to the air. Due to coupling of C_O and Φ that occurs only via boundary conditions at the cathode, concentration polarisation is automatically taken into account.

The system of partial differential equations governing the corrosion process will numerically be solved for the axi-symmetric problem by means of the finite element method in the spatial domain and using finite difference method in the time domain. The domain in which the problem will be solved is shown in *Fig. 1.*

Results and Discussion

The dependence of oxygen diffusivity (D_O) and electrical conductivity (σ) on the degree of water saturation (S), for good-quality concrete (w/c = 0.4) and for poor-quality concrete (w/c = 0.7), is presented in *Table 1.* Other parameters needed for the calculation of the corrosion current density are given in *Table 2.* It should be noted that the concentration of dissolved oxygen in the entire concrete sample at the moment of steel depassivation was assumed equal to that on the concrete surface.

Results of this evaluation for the corrosion current density ($i=-\sigma\nabla\Phi$) are shown in *Fig. 2.* The shape of the profile of the radial component of the corrosion current density (i_r) indicates where there is a risk for pitting corrosion which is unfavorable for reinforcing steel as its cross-section reduces very fast due to the large corrosion current density. These results are in agreement with previous calculations which have been obtained in a similar approach [12].

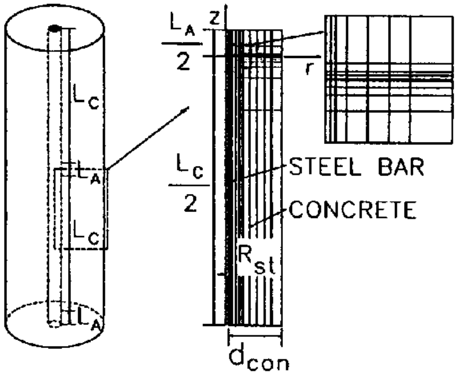

FIG. 1.
Domain in which the corrosion problem is to be solved.

Fig. 3 shows, for various w/c ratios of concrete and for various cover thicknesses of concrete, maximum values of radial components of the corrosion current density, depending on the degree of water saturation. Results shown in *Fig. 3* clearly indicate that the corrosion current density reduces less with the increase in cover thickness of the same concrete (concrete of the same quality) then by reducing the w/c ratio of concrete from 0.7 to 0.4 (i.e. by improving the concrete quality or reducing the permeability).

Due to the opposite effect of moisture content on the oxygen diffusion coefficient and on the electric conductivity of concrete, there is a state of concrete in which the steel corrosion rate is highest. This state of concrete should be avoided in practice. After exceeding a degree of water saturation which defines this state, the reaction rate at the cathode surface becomes much

TABLE 1
Dependence of D_0 and σ on the Degree of Water Saturation [4, 5]

w/c = 0.4						
S/%	35	40	42.5	45	47.5	50
D_0/cm^{2}day^{-1}	29	23.8	21.2	18.6	16	13.4
σ/Ω^{-1}cm^{-1}	1×10^{-7}	2.5×10^{-7}	5×10^{-7}	7×10^{-7}	13×10^{-7}	20×10^{-7}
w/c = 0.7						
S/%	32.5	35	37.5	40	42.5	45
D_0/cm^{2}day^{-1}	102.8	99.4	95.9	92.4	88.9	85.4
σ/Ω^{-1}cm^{-1}	4×10^{-6}	5×10^{-6}	7.5×10^{-6}	1×10^{-5}	1.4×10^{-5}	1.8×10^{-5}
Note: Values for σ for S < 40% were obtained by extrapolation.						

TABLE 2
Numerical Values for Evaluation of Corrosion Current Density

$R_{st} = 0.6$ cm; $d_{con} = 10$ cm and $d_{con} = 5$ cm

$L_A = 10$ cm; $L_C = 100$ cm

$k_3 = 8.29 \times 10^{-5}$ g/C; $k_4 = 4.15 \times 10^{-5}$ g/C [1]

$\varepsilon = 3.7\%$ for w/c = 0.4; $\varepsilon = 9.6\%$ for w/c = 0.7

$C_0^{sea} = 7.2 g/m^3$ [11]

$C_0 (r,z,t_p) = \varepsilon C_0^{sea} = 0.27 g/m^3$ for w/c = 0.4

$C_0 (r,z,t_p) = \varepsilon C_0^{sea} = 0.69 g/m^3$ for w/c = 0.7

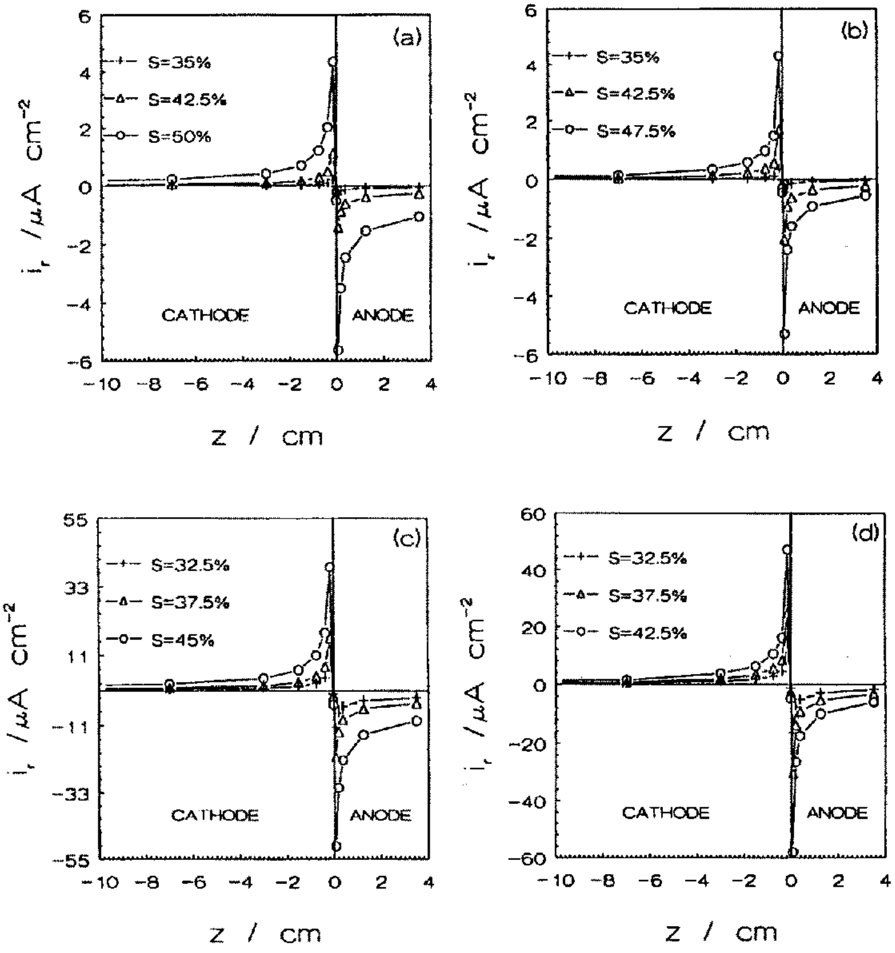

FIG. 2.
Profile of radial component of corrosion current density at electrode surfaces: (a) w/c = 0.4, d_{con} = 10cm; (b) w/c = 0.4, d_{con} = 5 cm; (c) w/c = 0.7, d_{con} = 10 cm; (d) w/c = 0.7, d_{con} = 5 cm.

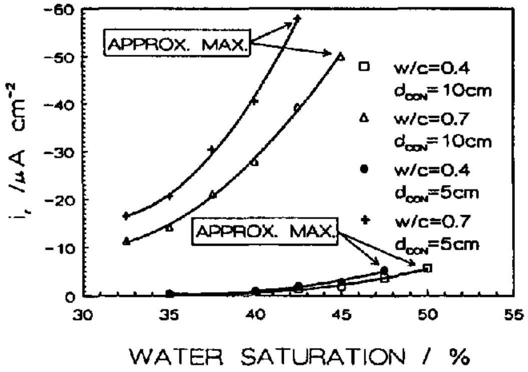

FIG. 3.
Influence of water-cement ratio, concrete cover and water saturation on corrosion current density.

faster than the rate of oxygen transport to the electrode. In such a state, the mixed cathodic-ohmic governed corrosion process becomes a diffusion governed process, and the corrosion current density decreases down to the oxygen limiting value. The threshold values for water saturation is determined from diagrams which are presented in *Fig. 4*.

A similar conclusion to this was obtained in previous experimental work in which corrosion rates are presented as a function of the degree of water saturation [13].

Conclusion

The conclusions that can be drawn from the study presented here are as follows:

- The profile of the radial component of the corrosion current density, obtained under specific conditions of corrosion analysis in the concrete, indicates if there is a risk for pitting corrosion.
- If other parameters are constant, the change in concrete quality expressed through the reduction in w/c ratio influences much more the corrosion current density value than an increase of thickness (from 5 to 10 cm) of the concrete cover of the same quality.
- For the conditions considered in this steel corrosion analysis, the maximum of corrosion rate is reached in the following cases:

w/c = 0.4; d_{con} = 10 cm: S = 45 - 50 %
w/c = 0.7; d_{con} = 10 cm: S = 40 - 45%
w/c = 0.4; d_{con} = 5 cm: S = 45 - 47.5%
w/c = 0.7; d_{con} = 5 cm: S = 37.5 - 42.5%

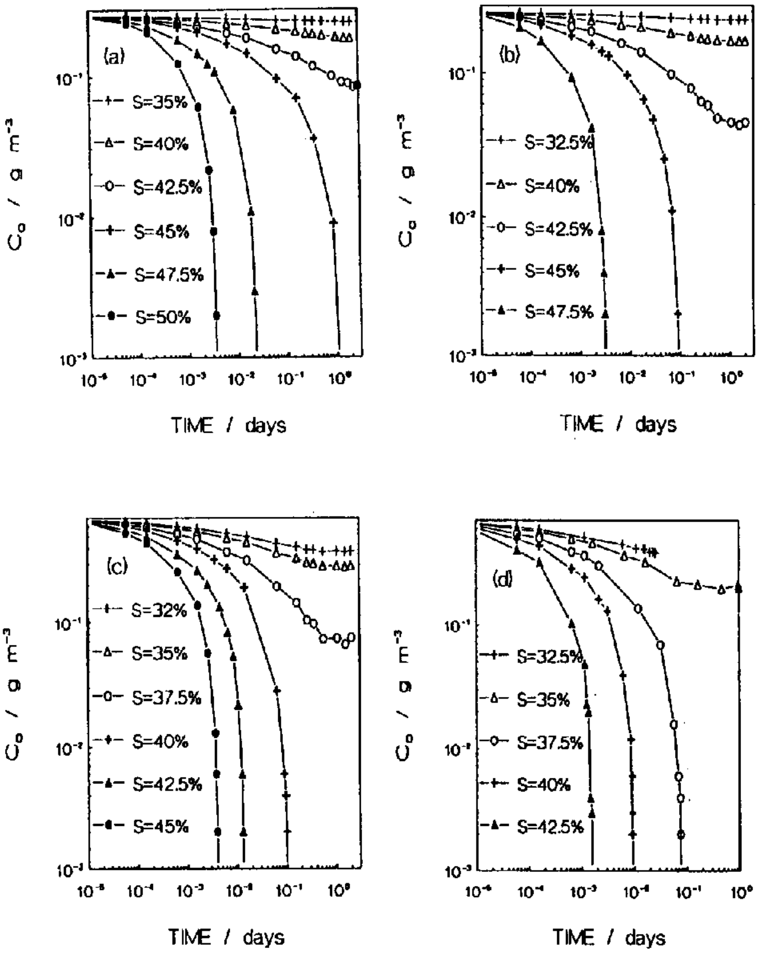

FIG. 4.

Influence of water saturation on the dissolved oxygen concentration at the cathode surface for node nearest to the anode: (a) w/c = 0.4, d_{con} = 10 cm; (b) w/c = 0.4, d_{con} = 5 cm; (c) w/c = 0.7, d_{con} = 10 cm; (d) w/c = 0.7, d_{con} = 5 cm.

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