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Probabilistic Models for Chloride-Induced Reinforcement Corrosion in Nuclear Power Plant Concrete Structures

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1. Introduction

The management of age-related degradation of concrete safety-related structures and passive components in nuclear plants has recently been recognized as one of the major challenges to extend plant service life more than sixty years.

Chloride-induced corrosion of the reinforcing steel is known to be a major cause of weakening the structural safety function of concrete structures. Since the degree of reinforcement corrosion is closely related to the deterioration of structural capacity, an accurate prediction of corrosion loss of reinforcement can assist structural engineers in achieving an effective management of concrete structures.

It is practically impossible to obtain exact input values for predicting corrosion of reinforcement in concrete structures. The input parameters are random variables. Thus, in order to account for the variability of input variables in predicting the corrosion process of reinforcement, a probabilistic approach can be utilized.

2. Chloride-Induced Corrosion Models

The chloride-induced corrosion of reinforcing steel in concrete has two distinct time periods. The first is the time for chloride to reach the surface of reinforcing steel and initiate corrosion. The second is the time period from the initiation of corrosion to corrosion induced unserviceability of the structure**.**

2.1 Corrosion Initiation

The corrosion initiation is mainly dependent on the chloride concentration, cover depth, crack opening and porosity of covering concrete.

If it is assumed that the corrosion of embedded steel is controlled by the diffusion of chloride ions, and that the concentration of chloride ions near the surface of the reinforcement is constant, the corrosion initiation time is given by [1]

$$T_{corr} = \frac{d_c^2}{4D_{av}}\left[erf^{-1}\left(1-\frac{C_{cr}}{C_s}\right)\right]^{-2} \qquad (1)$$

where, T_{corr} is the corrosion initiation time (years), d_c is the concrete cover (mm), D_{av} is the average chloride diffusion coefficient (mm^2/year) given by, C_{cr} is the critical chloride concentration at which corrosion begins, C_s is the equilibrium chloride concentration at the concrete surface, and *erf* is the statistical error function.

The diffusion coefficient of concrete mainly depends on the water-to-cement ratio (*w/c*), and the diffusion coefficient of the uncracked concrete, D_0, can be estimated with a simple formula as follows [2]:

$$D_0\left(\mathrm{m^2/s}\right) = 30.83\left(w/c\right)^{3.5} \times 10^{-12} \qquad (2)$$

When a crack occurs in cover concrete, it may accelerate the initiation of reinforcement corrosion. For cracked concrete components, the average diffusion coefficient, D_{av}, can be expressed as [3]:

$$D_{av} = \left(31.61 w_{cr}^2 + 4.73 w_{cr} + 1\right)\cdot D_0, \quad w_{cr} \ge 0.1\,\mathrm{mm} \qquad (3)$$

where, w_{cr} is the crack width (mm) and D_0 is the diffusion coefficient of the uncracked concrete

2.2 Corrosion Propagation

Once corrosion has been initiated, the cross sectional area of reinforcement decreases, with time, at a rate which is dependent on the corrosion rate and diameter of the individual bars. The diameter of the reinforcement at a time *t* for given corrosion initiation time T_{corr} can be determined by [4]

$$d_b(t,T_{corr}) = \begin{cases} d_{b0} & \text{for } t \le T_{corr} \\ d_{b0} - \dfrac{1.0508(1-w/c)^{-1.64}}{d_c}(t-T_{corr})^{0.71} & \text{for } T_{corr} < t \le T_f \\ 0 & \text{for } t > T_f \end{cases} \qquad (4)$$

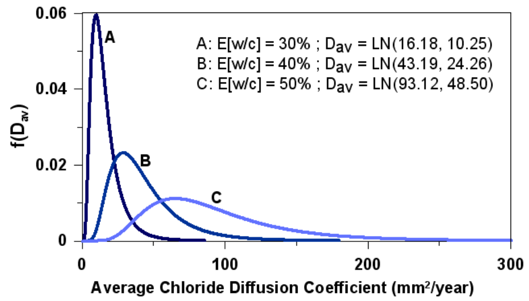
where, d_{b0} is the diameter of the reinforcement at a time t = 0 (cm), *w/c* represents the water-to-cement ratio, d_c is the concrete cover (cm), and T_f is the time when $d_b(t,T_{corr})$ reaches zero (year), that is $T_f = T_{corr} + \left[d_{b0}\cdot d_c / \left\{1.0508(1-w/c)^{-1.64}\right\}\right]^{1/0.71}$.

3. Corrosion Prediction

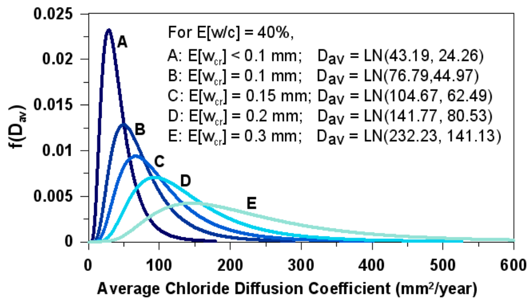
The probabilistic models for chloride-induced corrosion of reinforcement were obtained by Monte Carlo simulation. The values of basic stochastic variables are presented in Table I. As a result, the effect of water cement ratio and crack width on the average diffusion coefficient is shown in Fig. 1. The corrosion initiation time and the time when reinforcement diameter reaches zero for different surface chloride concentrations and crack widths are presented in Figs. 2 and 3.

Table I: Values of Basic Variables used in Corrosion Prediction

Variable	Unit	Mean	COV	Distribution
d_c	mm	59.5	0.3	Lognormal
C_{cr}	wt % conc	0.03	0.2	Lognormal
w/c	%	40	0.15	Lognormal
d_b	mm	35.7	0.15	Lognormal

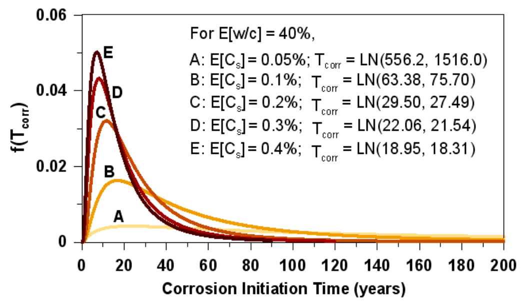


(a) D_{av} vs. w/c

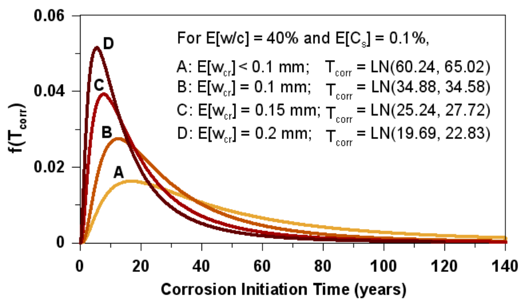


(b) D_{av} vs. w_{cr}

Fig. 1. Effect of water cement ratio and crack width on average diffusion coefficient.



(a) T_{corr} vs. C_s



(b) T_{corr} vs. w_{cr}

Fig. 2. Corrosion initiation time for different surface chloride concentrations and crack widths.

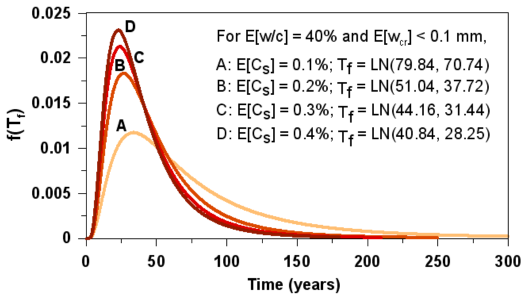


Fig. 3. Effect of surface chloride concentration on the time when diameter of reinforcement reaches zero.

In Fig. 1, it can be seen that an increase in the mean values of the water cement ratio and surface crack width causes an increase in the average chloride diffusion coefficient. Fig. 2 shows that as the mean value of the surface chloride concentration and crack width increases, the mean corrosion initiation time decreases quickly. Fig. 3 represents that an increase of surface chloride concentration can reduce the structural capacity of reinforced concrete structures and components. Moreover, it should be noted that an increase of surface crack may significantly decrease the service life of concrete structures.

4. Conclusions

The chloride-induced corrosion of reinforcement in concrete structures can be predicted by lognormal distribution. The proposed simple models can be used for evaluating the structural capacity of concrete structures in nuclear power plants. In order to obtain more realistic models, a large number of reliable data should be collected through field survey and experiment.

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