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Chloride-induced corrosion of reinforced concrete bridge decks

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Abstract

A closed-form solution is developed to predict the corrosion initiation time of reinforced concrete bridge decks using measured time varying surface chloride accumulations. The data base for the surface chlorides are core measurements at a shallow depth below the surface of 15 bridge decks in the snow belt region. The data base was collected during the bridges' biennial inspections over a period of 15 years. Regression analysis is used to represent the surface chlorides by an exponential variation with time. The time predicted to initiate corrosion is computed for different values of the effective diffusion coefficient and the concrete cover thickness. The results are compared to the constant surface accumulation model commonly used in the literature. As expected, the corrosion initiation based on constant chloride accumulation at the surface is faster (in some case by up to 100%) than the initiation time calculated from actual chloride concentration data. Such results are useful for the realistic estimation of the service lives of bridge decks and for scheduling bridge deck maintenance and rehabilitation programs.

Keywords: Corrosion; Diffusion; Chloride; Reinforcement; Concrete

1. Introduction

Corrosion of reinforcing steel bars in concrete members is an electrochemical reaction between the steel and its surrounding environment. According to one leading theory, it occurs whenever the oxide film, formed during cement hydration and maintained by the high alkalinity of the concrete ($\mathrm{pH} < 12.5$), is broken by the intrusion of chloride ions. In concrete bridge decks, chloride ions are derived mainly from deicing salts used during winter maintenance operations and from exposure to sea water. The chlorides in the salt penetrate the concrete and, when they reach a critical concentration, they break the passive film surrounding the reinforcing steel, and corrosion is initiated.

In this paper, a closed-form solution is developed to predict the corrosion initiation time of reinforced concrete bridge decks using measured time varying surface chloride accumulations. The data base for the surface chlorides are core measurements at a shallow depth below the surface of 15 bridge decks in the snow belt region [1]. The data base provided in Ref. [1] was collected during the bridges' biennial inspections over a period of 15 years. Actual data for specific bridge decks show that for new decks, the chloride concentration initially fluctuates about a steadily rising level, and then after about 10–15 years, the chloride concentration near the top surface of the deck continues to increase with time at a slower rate. The variability in the data about an increasing average value is to be expected since the concentration of chloride ions at the surface varies with the number of deicing applications and the cycles of wetting and drying. In this paper, a regression analysis is used to develop analytical expressions to describe the variation of the surface chloride content with time. These expressions are used as surface conditions and a closed-form solution of the applicable diffusion equation is presented. Corrosion will initiate when the concentration of chlorides around the reinforcing steel reaches a critical value. Since the cover thickness to the top reinforcing bars, d, and the diffusion coefficient, D_0, vary from deck to deck, the time required to initiate corrosion is predicted for a wide range of values of d and D_0. The results obtained from the realistic surface chloride concentrations are compared to the initiation time predicted assuming constant concentrations. The corrosion initiation time based on constant chloride accumulation at the surface is shown to be faster than the

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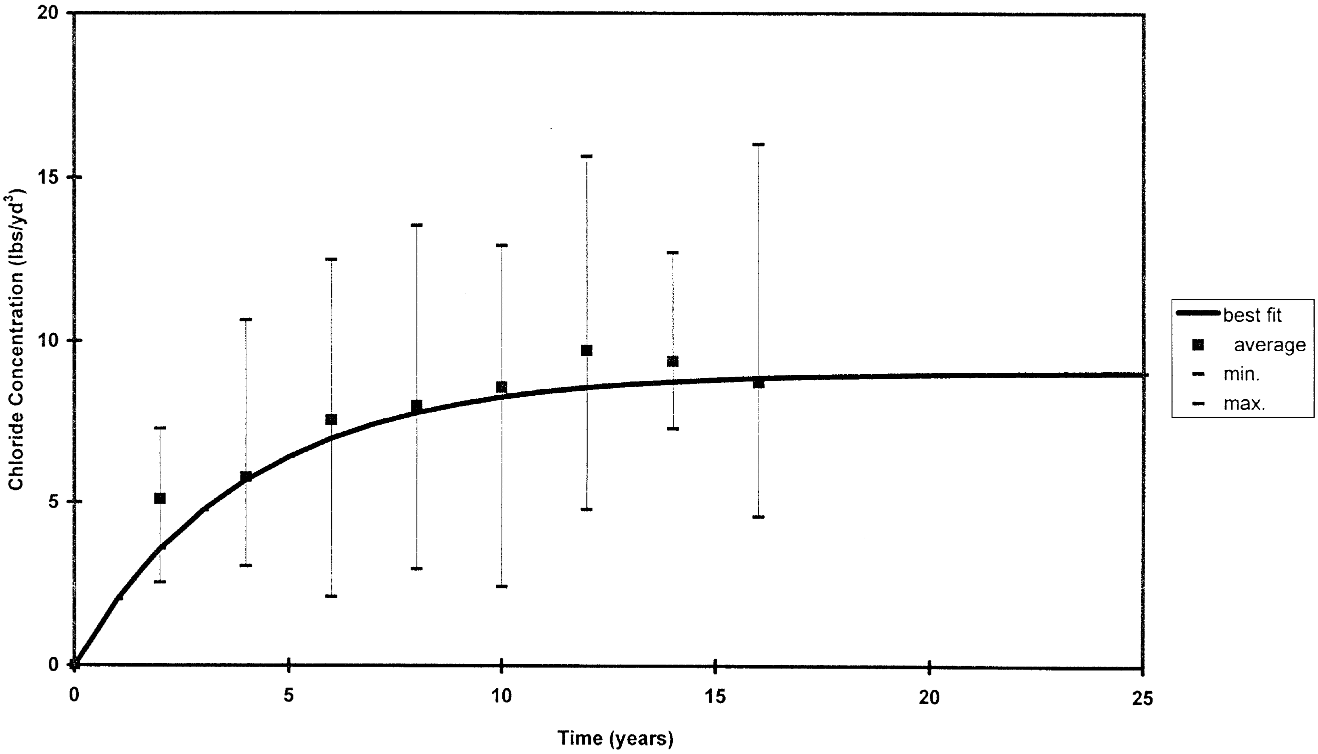

Fig. 1. Exponential representation of the surface chloride data.

initiation time corresponding to the actual test data. Such results are useful for the realistic estimation of the service lives of bridge decks in snow belt regions and for scheduling bridge deck maintenance and rehabilitation programs.

2. Time-varying chloride concentration model

It is widely accepted that the diffusion of chloride ions through an uncracked deck's surface may be modeled by the one-dimensional Fick's law for isotropic medium, namely:

$$\frac{\partial C}{\partial t} = D_0 \frac{\partial^2 C}{\partial x^2} \tag{1}$$

where $C(x,t)$ is the concentration of chloride ions at distance x from the surface, t is the time of exposure to the chloride source, and D_0 is the diffusion coefficient.

In the literature, most authors assume constant chloride accumulation at the surface, i.e., a constant $[C(0,t) = C_0]$ is used as the surface exposure condition when solving Eq. (1) (e.g., Refs. [2,3]). In this case, the time to initiate corrosion, t_i, is given as:

$$t_\mathrm{i} = \frac{d^2}{4D_0} \frac{1}{\left[\mathrm{erf}^{-1}\left(1 - \frac{C_\mathrm{cr}}{C_0}\right)\right]^2} \tag{2}$$

where erf( ) is the standard error function [4], d is the concrete cover, and C_cr is the threshold value of $C(x,t)$, assumed in this paper as $C_\mathrm{cr} = 5.818$ N/m^3 (1.0 lb/yd^3).

Data collected in the field show that the constant chloride model described above is not necessarily accurate. As an example, the data collected by Weyers et al. [1] from 15 bridge decks in the snow belt region over a 15-year period are shown in Fig. 1. Fig. 1 plots the mean value as a function of time (as well as the high and low) of the chloride concentration at a depth of 6.35 mm (0.25 in.) for 15 different decks. The figure clearly shows that the average value of the surface chloride accumulation increases with time and that the surface chloride concentration can be conveniently represented by an exponential function of time. A regression analysis of the field data produces an equation of the form:

$$C(0,t) = C_0[1 - \mathrm{e}^{-\alpha t}] \tag{3}$$

where $C_0 = 52.362$ N/m^3 (9 lb/yd^3), $\alpha = 0.25$ (year^{-1}), and t is the time measured in years. The regression analysis gives a coefficient of determination R^2 of the order of .62. This indicates that 38% of the variation in the data is unexplained by the regression curve. This unexplained variation might be due to the extent of deicing, the wetting and drying cycles, and other seasonal and site-specific effects.

Using Eq. (3), the solution of Eq. (1) with zero concentration at time $t = 0$ is [5]:

$$\frac{C(x,t)}{C_0} = 1 - \mathrm{erf}\left(\frac{x}{\sqrt{4D_0t}}\right) - \frac{1}{2}\mathrm{e}^{-\alpha t}\left[\mathrm{e}^{-x^2\left(-\frac{\alpha}{D_0}\right)^{1/2}}\mathrm{erfc}\left(\frac{x}{\sqrt{4D_0t}} - (-\alpha t)^{1/2}\right) + \mathrm{e}^{x^2\left(-\frac{\alpha}{D_0}\right)^{1/2}}\mathrm{erfc}\left(\frac{x}{\sqrt{4D_0t}} + (-\alpha t)^{1/2}\right)\right] \tag{4}$$

where erfc(x) is the complement of the error function defined as erfc(x) = 1 − erf(x). Introducing the variable, z, such that (Eq. (5)):

$$z = (\alpha t)^{1/2} + i\frac{x}{\sqrt{4D_0t}} \tag{5}$$

where $i = (-1)^{1/2}$ is the usual complex number, it is readily shown that Eq. (4) can be expressed as (Eq. (6)):

$$\frac{C(x,t)}{C_0} = 1 - \mathrm{erf}\left(\frac{x}{\sqrt{4D_0t}}\right) - \mathrm{e}^{-\frac{x^2}{4D_0t}}\mathrm{Re}\left[\mathrm{e}^{-z^2}\mathrm{erfc}(-iz)\right] \tag{6}$$

where Re[ ] stands for the real part of function [ ].

When $C(x,t)$ reaches the threshold value, $C_{cr} = 5.818$ N/m^3 (1.0 lb/yd^3), at the depth of the reinforcement steel, $x = d$ mm (inches), the time (year) at which corrosion commences can be computed by finding the roots of the transcendental equation for given values of d and D_0:

$$\mathrm{erf}\left(\frac{d}{\sqrt{4D_0t}}\right) + u\,\mathrm{e}^{-\frac{d^2}{4Dt}} = 1 - \frac{C_{cr}}{C_0} \tag{7}$$

where $u(z)$ is the real part of the function $e^{-z^2}\mathrm{erfc}(-iz)$.

3. Results

The roots of Eq. (7) can be obtained using a suitable numerical method such as a Newton–Raphson algorithm. The results appear in Table 1 for a typical range of values of the cover d and the diffusion coefficient D_0. Table 1 contains the time (in years) estimated to initiate corrosion using Eqs. (2) and (7) for bridge decks with cover thickness, d, varying between 44.45 and 76.2 mm (1.75 and 3.00 in.) and a constant diffusion coefficient, D_0, varying between 39.5 and 131.6 mm^2/year (0.06 and 0.20 in.^{2}/year). The time to initiate corrosion predicted from Eq. (2), which is based on the assumption that the surface chloride content is constant, is given in the first row of the table. The time predicted using the regression model of the actual test data, represented by Eq. (7), is given in the second row of the table. As expected, corrosion initiation based on constant chloride accumulation at the surface is predicted to be faster than the initiation time corresponding to the model based on the actual test data for all the cases considered. The constant surface exposure model is more conservative producing lower-bound estimates of the time to initiate corrosion, while Eq. (7) provides more reasonable "average" results. For cases of low values of D_0 and thick covers, the time to initiate corrosion is high, and in these cases the exponential surface concentration produces times to initiate corrosion that asymptotically approach the times predicted by the constant concentration curve. On the other hand, for high values of D_0 and thin covers, the exponential curve predicts almost double the time required to initiate corrosion. Specifically, the difference is almost 90 to 100% for $d = 44.45$ mm (1.75 in.) and 50.8 mm (2.00 in.) and high values of diffusion coefficient, D_0.

Table 1
Time predicted to initiate corrosion (year)–constant diffusivity for an average site

		d (in.)[b]					
D_0 (in.^{2}/year)[a]	Surface condition ($f(t)$)	1.75	2.00	2.25	2.50	2.75	3.00
0.06	Eq. (2)—constant	10.1	13.1	16.6	20.5	24.8	29.6
	Eq. (7)—exponential	13.8	17.0	20.5	24.5	28.8	33.5
0.08	Eq. (2)—constant	7.5	9.9	12.5	15.4	18.6	22.2
	Eq. (7)—exponential	11.1	13.6	16.3	19.3	22.6	26.1
0.10	Eq. (2)—constant	6.0	7.9	10.0	12.3	14.9	17.7
	Eq. (7)—exponential	9.4	11.5	13.7	16.1	18.8	21.7
0.12	Eq. (2)—constant	5.0	6.6	8.3	10.3	12.4	14.8
	Eq. (7)—exponential	8.3	10.0	11.9	14.0	16.2	18.7
0.14	Eq. (2)—constant	4.3	5.6	7.1	8.8	10.6	12.4
	Eq. (7)—exponential	7.5	9.0	10.6	12.4	14.4	16.5
0.16	Eq. (2)—constant	3.7	4.9	6.2	7.7	9.3	11.1
	Eq. (7)—exponential	6.8	8.2	9.7	11.3	13.0	14.9
0.18	Eq. (2)—constant	3.4	4.4	5.5	6.8	8.3	9.9
	Eq. (7)—exponential	6.3	7.5	8.9	10.3	11.9	13.6
0.20	Eq. (2)—constant	3.0	3.9	5.0	6.2	7.5	8.9
	Eq. (7)—exponential	5.9	7.0	8.3	9.6	11.0	12.5

[a] 1 in^2/year = 645 mm^2/year.

[b] 1 in. = 25.4 mm.

The results are further illustrated in Fig. 2 that shows how the time to initiate corrosion varies as a function of the diffusion coefficient, D_0. Four curves are presented depicting the effects of the cover depth, d, and the chloride concentration model used. The cover depths used in Fig. 2 are for 44.45 mm (1.75 in.) and 76.2 mm (3.00 in.). For each cover depth, the results from the constant chloride concentration model (Eq. 2) are compared to those of the exponentially varying chloride concentration model (Eq. 7). The results of Fig. 2 further illustrate the large conservativeness associated with using the constant concentration model for predicting the time required to initiate corrosion as compared to the more realistic time-varying concentration model.

The numerical calculations executed above were based on a "fictitious" site data having the "average" characteristics from all the 15 sites analyzed by Weyers et al. [1]. The results from two "extreme sites" are also analyzed and their results are presented in Tables 2 and 3. The first site is

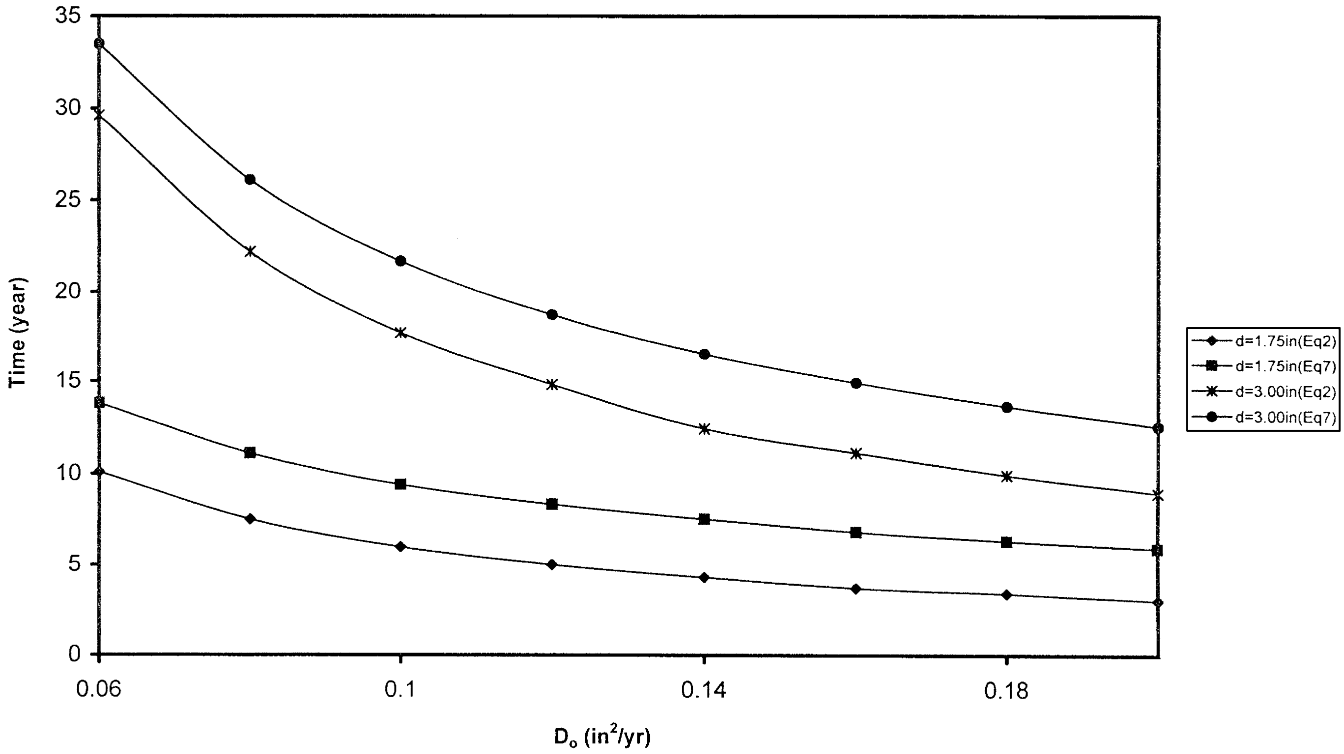

Fig. 2. Time to corrosion initiation as a function of diffusion coefficient (D_0) and cover depth (d).

chosen to have a high level of chloride concentration while the second site is chosen to have low level of chloride concentrations. Fitting the measured chloride concentrations from these two sites through curves of the form of Eq. (3) produced a constant C_0 value equal to 69.82 N/m^3 (12 lb/yd^3) for the site with high concentrations and a C_0 value equal to 23.27 N/m^3 (4 lb/yd^3) for the site with low concentration. Both cases are associated with an exponent $\alpha = 0.25$ (year^{-1}). The results provided in Tables 2 and 3 show similar trends to those observed for the "fictitious average" site studied in the previous paragraph. Specifically, the difference between the results assuming a constant concentration of chlorides and those obtained assuming time varying concentrations is close to 100% for the cases when the cover thickness is small and the diffusion coefficient is high. Thus, it is important to include the effect of the

Table 2
Time predicted to initiate corrosion (year)–constant diffusivity for site with low level of exposure to chlorides

		d (in.)[b]					
D_0 (in.^{2}/year)[a]	Surface condition ($f(t)$)	1.75	2.00	2.25	2.50	2.75	3.00
0.06	Eq. (2)—constant	19.3	25.2	31.9	39.3	47.6	56.6
	Eq. (7)—exponential	23.6	29.5	36.0	43.3	51.3	60.0
0.08	Eq. (2)—constant	14.5	18.9	23.9	29.5	35.7	42.5
	Eq. (7)—exponential	18.8	23.2	28.2	33.7	39.8	46.3
0.10	Eq. (2)—constant	11.6	15.1	19.1	23.6	28.6	34.0
	Eq. (7)—exponential	15.9	19.5	23.5	27.9	32.8	38.1
0.12	Eq. (2)—constant	9.6	12.6	15.9	19.7	23.8	28.3
	Eq. (7)—exponential	13.9	16.9	20.3	24.0	28.1	32.5
0.14	Eq. (2)—constant	8.3	10.8	13.7	16.9	20.4	24.3
	Eq. (7)—exponential	12.5	15.1	18.0	21.2	24.7	28.6
0.16	Eq. (2)—constant	7.2	9.4	12.0	14.8	17.9	21.2
	Eq. (7)—exponential	11.4	13.7	16.3	19.1	22.2	25.6
0.18	Eq. (2)—constant	6.4	8.4	10.6	13.1	15.9	18.9
	Eq. (7)—exponential	10.6	12.6	14.9	17.5	20.2	23.2
0.20	Eq. (2)—constant	5.8	7.6	9.6	11.8	14.3	17.0
	Eq. (7)—exponential	9.9	11.8	13.9	16.1	18.6	21.4

[a] 1 in^2/year = 645 mm^2/year.
[b] 1 in. = 25.4 mm.

Table 3
Time predicted to initiate corrosion (year)–constant diffusivity for site with high level of exposure to chlorides

		d (in.)[b]					
D_0 (in.^{2}/year)[a]	Surface condition ($f(t)$)	1.75	2.00	2.25	2.50	2.75	3.00
0.06	Eq. (2)—constant	8.5	11.1	14.1	17.4.	21.0	25.0
	Eq. (7)—exponential	12.0	14.7	17.8	21.2	24.9	28.9
0.08	Eq. (2)—constant	6.4	8.3	10.6	13.0	15.8	18.8
	Eq. (7)—exponential	9.6	11.8	14.1	16.7	19.5	22.6
0.10	Eq. (2)—constant	5.1	6.7	8.4	10.4	12.6	15.0
	Eq. (7)—exponential	8.2	10.0	11.9	14.0	16.3	18.8
0.12	Eq. (2)—constant	4.3	5.6	7.0	8.7	10.5	12.5
	Eq. (7)—exponential	7.2	8.7	10.4	12.2	14.1	16.2
0.14	Eq. (2)—constant	3.7	4.8	6.0	7.4	9.0	10.7
	Eq. (7)—exponential	6.5	7.8	9.2	10.8	12.5	14.3
0.16	Eq. (2)—constant	3.2	4.2	5.3	6.5	7.9	9.4
	Eq. (7)—exponential	5.9	7.1	8.4	9.8	11.3	12.9
0.18	Eq. (2)—constant	2.8	3.7	4.7	5.8	7.0	8.3
	Eq. (7)—exponential	5.5	6.5	7.7	9.0	10.3	11.8
0.20	Eq. (2)—constant	2.6	3.3	4.2	5.2	6.3	7.5
	Eq. (7)—exponential	5.1	6.1	7.2	8.3	9.5	10.9

[a] 1 in^2/year = 645 mm^2/year.
[b] 1 in. = 25.4 mm.

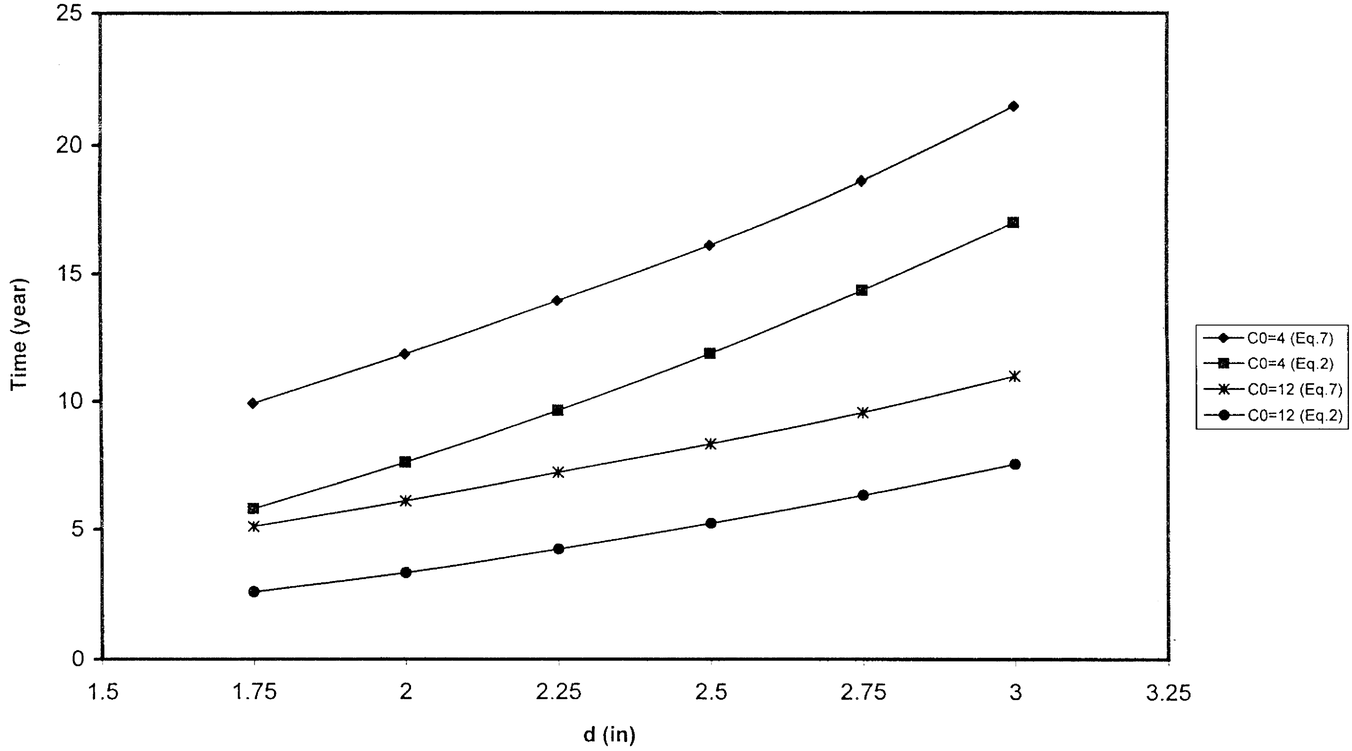

Fig. 3. Time to corrosion initiation as a function of cover depth (*d*) for different chloride concentration levels, $D_0 = 0.20$.

variation of the chloride concentrations with time as the safety analysis of bridge decks for corrosion is performed.

In addition, by comparing the results of Tables 1, 2, and 3, it is observed that the difference between the time to initiate corrosion is also as high as 100% between decks exposed to low levels of chlorides and high concentrations of chlorides. Hence, it is very important to include the level of a deck's exposure to chlorides when analyzing its safe design life. The results of Tables 2 and 3 are also illustrated in Fig. 3, which depicts the change in the time to initiate corrosion as a function of the cover depth, *d*, for a diffusion coefficient, $D_0 = 129$ mm^2/year (0.20 in.^{2}/year), and different values of chloride concentrations, C_0. The figure reveals the difference between the corrosion initiation time when using the constant chloride concentration model of Eq. (2) and the exponential model of Eq. (7) for two concentration levels $C_0 = 23.27$ N/m^3 (4 lb/yd^3) and $C_0 = 69.82$ N/m^3 (12 lb/yd^3). The plots also show the large difference in the time to corrosion initiation between the decks subjected to low levels of chlorides and large levels of chlorides. Similar trends as those of Fig. 3 are observed for different diffusion coefficients, D_0, and different chloride concentrations, C_0.

4. Concluding remarks

The results presented in this paper show the importance of using realistic data of surface chloride concentrations as compared to assuming constant levels of surface chlorides when estimating the effective design life of bridge decks. Although the latter model gives conservative estimates on the time to corrosion initiation, the error in using the constant concentration model may reach as high as 100%. In addition, large differences of up to 100% are observed in the time for corrosion initiation between sites exposed to low concentrations of chlorides and those exposed to high concentrations. Therefore, it is important to account for the levels of chloride concentrations and the variation of these concentrations with time when estimating the safe design life of bridge decks.

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