

# Service Life Evaluation of Concrete Surface Coatings

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The use of surface coatings for concrete bridge substructures is one of the methods used as corrosion protection. The results of a 1-year laboratory study on three generic coatings, epoxy, urethane, and methyl methacrylate (MMA), are presented. Specimens were built to simulate four exposure conditions typical for concrete bridges located in the coastal region or inland where deicing salts are used. The exposure conditions were horizontal surface, vertical surface, tidal zone, and immersion zone. The service life of each coating was estimated on the basis of chloride ion diffusion through the coating and concrete. The diffusion equation for the condition that the surface chloride concentration changes as a function of the square root of time was used to estimate the service lives of the coatings for various component exposure conditions and the range of environmental exposure conditions in the United States.

The number of bridges in the United States was estimated to be 578,218 in the late 1980s (1). According to the U.S. Department of Transportation about 40 percent of these bridges were either structurally deficient or functionally obsolete (2).

A major cause of the deterioration of concrete bridge structures is associated with corrosion of the reinforcing steel. During the 1960s most states introduced a "bare road policy," which resulted in a significant increase in deicer salt applications (3). Because of the salting as well as the exposure to the salt water in the coastal regions, a large number of concrete bridges are contaminated with chlorides, which initiate the corrosion of the reinforcing steel. The resulting presence of chlorides and the loss of the alkaline environment cause the embedded steel to lose its surface passivity. Corrosion follows as water and oxygen become available to the steel. Accumulated corrosion products, which occupy more volume than the reactants, cause cracking of the protective concrete cover. This allows for the intrusion of chlorides and oxygen at a much faster rate, thus accelerating the corrosion process. Deterioration caused by the corrosion of reinforcing steel is not limited to bridge decks only. It can also affect other bridge members such as piles, walls, diaphragms, girders, abutments, piers, and pier caps (4).

Application of coatings on surfaces of concrete elements is one of the methods used to delay the deterioration process. The term *coating* refers to such surface treatment that forms a film on the surface of concrete and that penetrates the concrete little or not at all (5). Coatings' surface thicknesses range from 25  $\mu\text{m}$  to 1 mm (6). Although there are only several generic groups of coatings (epoxies, polyurethanes, acrylics, polyesters, etc.), the performances of two coatings from the same generic group may be very different; thus, the maintenance engineer needs to know how to evaluate the

performances of particular products. Since coatings form a layer on the surface their application is limited to substructure components and other elements that are not exposed to traffic wear. Their performance will be influenced by geographical location (coastal region, inland), average annual daily traffic (splash zone), average annual snowfall (deicing salts), and surface preparation of the concrete before coating application.

This paper presents the results of a 1-year study of three generic coatings: epoxy, methyl methacrylate (MMA), and polyurethane (urethane). The methodology used for service life (reapplication period) determination is also presented.

## EXPERIMENTAL DESIGN

For the present study three generic types of coatings were selected: epoxies, MMAs, and urethanes. The coatings were selected primarily on the basis of the coating's history (use of the product on concrete bridge substructures in the past), cost of materials (up to \$11.0/m<sup>2</sup>), and film thickness (from 375  $\mu\text{m}$  to 1 mm). The selected coatings are presented in Table 1.

Two specimens were used to assess the performance of the coatings. Each specimen (Figure 1) was covered with two coatings (or one coating and a control that was not coated). Specimen dimensions were 107 by 107 cm for the slab and 107 by 91 cm for each of the walls. The thicknesses for both walls and the slab were 10 cm. Cover depth over temperature/shrinkage reinforcement was designed to be 4.6 cm.

The concrete mixture used for the two specimens had the following properties: coarse aggregate, no. 7 (maximum aggregate size, 19 mm); water-cement ratio, 0.45; slump, 9 cm, and air content, 6 percent. Each sample was reinforced against concrete shrinkage with a mesh of 10-mm bars. The 28-day compressive strength was 40 MPa.

Since surface preparation is very important special care was taken during construction of the specimens. The specimens were wet cured for 1 week; this was followed by air dry curing for 3 weeks. Surfaces were sand-blasted because of contamination with form release agent and laitance. Small voids that appeared on the surfaces were then filled with mortar.

All coatings were applied by brushing and according to the manufacturers' specifications. Urethane was applied as one coat, with the dry thickness being approximately 625  $\mu\text{m}$ . Epoxy coating was applied in two, 200- $\mu\text{m}$ -thick coats. The MMA coating system consisted of three layers: the primer (penetrating sealer) and two top-coats (each approximately 200  $\mu\text{m}$  thick). The two specimens were then exposed to accelerated wet and dry cycles (ponding) with a 3 percent solution of sodium chloride. The specimens were designed

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**TABLE 1** Characteristics of Coatings

Coating type	Number of Coats:	Cost [\$ /m <sup>2</sup> ]	Coverage [m <sup>2</sup> /l]
Epoxy	two coats	3.77	6.1-7.4/coat
MMA	primer (penetrating sealer) two topcoats	9.04	2.5 4.9-6.1/coat
Urethane	one base coat	10.76	1.5-1.6

to represent four exposure conditions, as will be described. Since coatings are used only on bridge substructures the simulation of surface wear, typical for bridge decks, was not necessary. Also, ultraviolet light reaches bridge substructure elements in an amount much lower than that for superstructure elements (bridge decks). Thus, the specimens were housed inside the laboratory, where ultraviolet light exposure was a minimum.

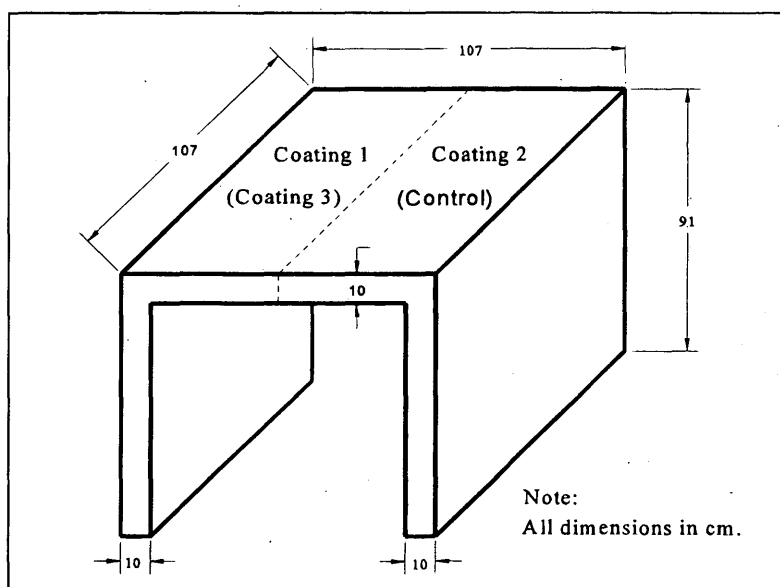
The horizontal section of the specimens (horizontal) simulated wetted surfaces such as the top surface of pier caps, diaphragms, and abutments. For this exposure condition an area of 0.57 m<sup>2</sup> (107 by 53 cm) was covered with each coating. The upper 53 cm of the specimens' legs (wall or vertical surface) simulated the vertical surfaces of abutments, pier caps, and piers. Each coating covered an area of 0.49 m<sup>2</sup> (53 by 91 cm). These two wall sections were exposed to 3 percent sodium chloride solution for 3 days and were allowed to air dry for 4 days during each 1-week ponding cycle. A vertical area between the 28th and the 38th cm from the bottom of specimens on the inner side of the specimens' legs (tide or tidal zone) simulated the tidal zones of concrete bridge substructures in coastal regions, with each tidal zone coating covering an area of 0.09 m<sup>2</sup>. These sections of specimens were exposed to immersion in 3 percent sodium chloride solution for 4 days and were then

allowed to air dry for 3 days during each 1-week ponding cycle. The very bottom section of the vertical sections (immersed zone) simulated concrete bridge substructures, piles, or piers in a coastal region immersed in seawater. Each immersion zone coating covered an area of 0.26 m<sup>2</sup>, from the bottom of the specimen's legs to a height of 28 cm. During the 1-week ponding cycle these areas were immersed in 3 percent sodium chloride solution for the entire period. The four exposure conditions are presented in Figure 2.

## DATA ANALYSIS

A coating's effectiveness was evaluated on the basis of chloride permeation through the concrete (and coatings). The chloride concentration was determined in accordance with the ASTM Standard Method [C-114, Section 19, Chloride (Reference Method)]. Measurements of chloride concentration were attained by collecting samples of pulverized concrete at three depths: 1.3, 2.5 and 3.8 cm. For each coating (and control) and for each exposure condition a set of three samples was taken at three locations. Each sample set consisted of samples from three depths, for a total of nine samples for each exposure condition at selected exposure times. Ten samples were taken to determine the background chloride concentration. Other samples for chloride content determination were collected after 7, 14, 21, 30, and 52 1-week ponding cycles. Each of these measurements included three samples for each coating (and control) at three depths for each exposure condition. The numbers of samples collected during the study are presented in Table 2.

The average background chloride content was 0.26 kg/m<sup>3</sup> of concrete. The average chloride concentration gain at a 1.3-cm depth for the control section varied from 5.69 kg/m<sup>3</sup> for the immersed zone exposure condition to 12.2 kg/m<sup>3</sup> for the wall exposure condition. The highest chloride concentration for coated surfaces was found

**FIGURE 1** Typical specimen.

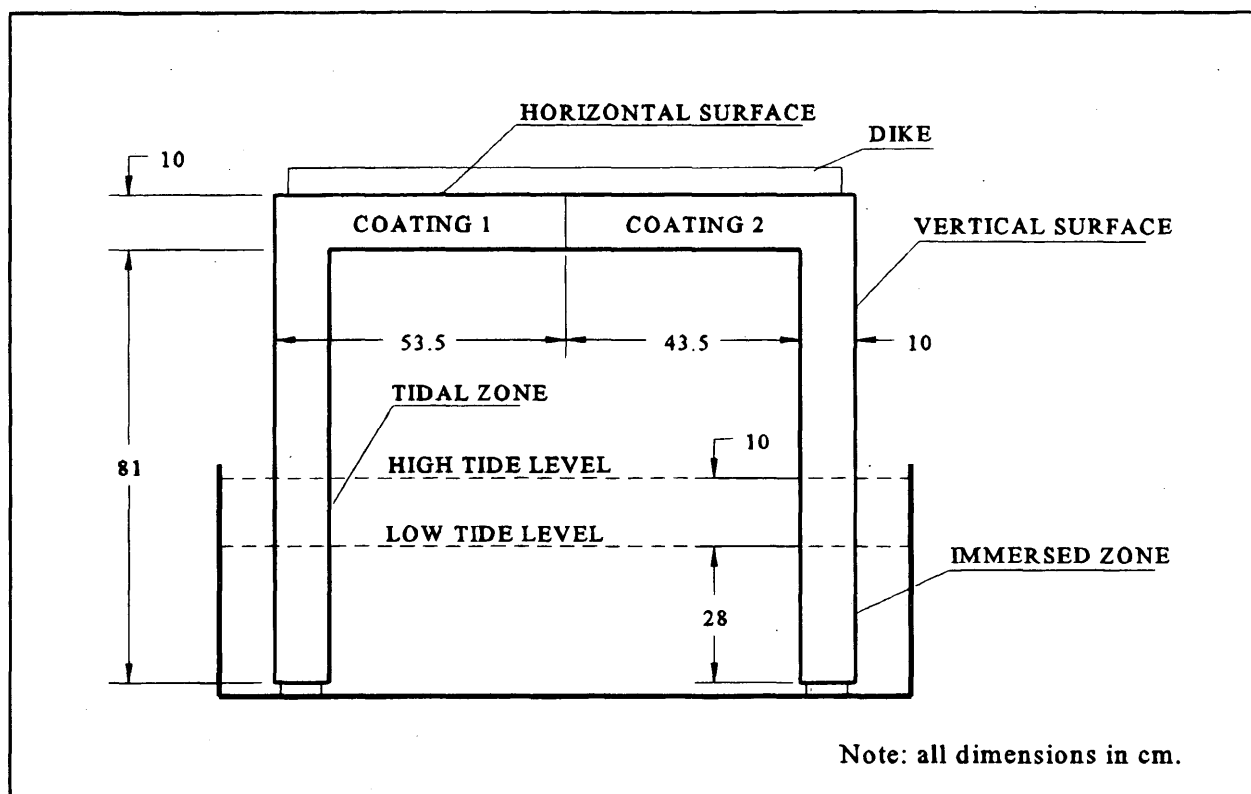


FIGURE 2 Exposure conditions.

with the epoxy coating in the tidal zone exposure condition (5.33 kg/m<sup>3</sup>). All results of the chloride content measurements for horizontal surface, vertical surface, tidal zone, and immersion zone conditions for the three tested coatings and the control are presented in Tables 3 to 5. The average gains in acid-soluble chloride concentrations above the background value over time for each coating and control at a 1.3-cm depth are given in Figures 3 to 6.

Visual observations for discoloring, blistering, and peeling were made each week. Peeling was observed on the specimen half covered with the MMA coating after every sampling session. The peeling was caused by the impact from the drill during the collection of powdered chloride content samples. Some blisters were observed on the urethane coating after only a couple of days following the coating application. It is believed that the blistering was caused by

entrapped air during coating application (the coating was applied as one thick coat in a very short time). After 1 year of testing the specimens were removed from the laboratory and were stored outdoors. After several freezing-thawing cycles (during the winter of 1994) the MMA coating had almost completely peeled off. The epoxy and urethane coatings remained intact during this outdoor exposure period.

## ANALYSIS AND DISCUSSION OF RESULTS

A regression analysis for the gain in chloride concentration for the 1.3-cm depth was performed and was found to be a function of the square root of time. Coefficients ( $k$ ) that represent the chloride ingress rate through the coated surfaces are presented in Table 6. The solution for the semi-infinite medium whose surface concentration varies with the function of time (square root) is obtained by the Laplace transform of the diffusion equation (7). The solution equation is as follows:

$$C_{(x,t)} = k \sqrt{t} \left[ e^{-x^2/4D_c t} - \frac{x\sqrt{\pi}}{2\sqrt{D_c t}} \left( 1 - \operatorname{erf} \frac{x}{2\sqrt{D_c t}} \right) \right] \quad (1)$$

where

$C$  = chloride concentration,

$D_c$  = diffusion constant,

$t$  = time,

$x$  = depth, and

$k$  = coating characteristics constant.

TABLE 2 Number of Samples

Number of One-Week Ponding Cycles	Number of Samples
0 (background)	10
7	108
14	144
21	144
30	144
52	144
Total	694

TABLE 3 Chloride Content Measurements at 1.3-cm Depth

Depth = 1.3 cm		Average Gain in Chloride Concentration [kg/m <sup>3</sup> ]					
Exposure	Coating	Number of One-Week Exposure Cycles					
		0	7	14	21	30	52
Immersed	Control	0.00	4.01	6.62	5.42	6.09	5.69
	Epoxy	0.00	1.34	1.75	1.78	0.88	1.39
	MMA	0.00	0.43	0.53	0.89	0.58	0.75
	Urethane	0.00	0.00	0.18	0.16	0.25	0.27
Tide	Control	0.00		6.05	8.52	9.10	9.83
	Epoxy	0.00		3.56	3.79	3.86	5.33
	MMA	0.00		0.33	0.45	0.37	1.03
	Urethane	0.00		1.58	2.12	1.70	3.66
Wall	Control	0.00	7.89	10.37	9.93	11.77	12.17
	Epoxy	0.00	3.75	1.60	1.73	1.73	1.85
	MMA	0.00	0.04	0.60	0.18	0.27	0.34
	Urethane	0.00	0.00	0.71	0.81	0.73	0.34
Horizontal	Control	0.00	7.52	9.10	8.99	9.34	11.43
	Epoxy	0.00	0.21	0.29	0.37	0.30	0.29
	MMA	0.00	0.05	0.03	0.09	0.12	0.21
	Urethane	0.00	0.00	0.04	0.15	0.14	0.21

TABLE 4 Chloride Content Measurements at 2.5-cm Depth

Depth = 2.5 cm		Average Gain in Chloride Concentration [kg/m <sup>3</sup> ]					
Exposure	Coating	Number of One-Week Exposure Cycles					
		0	7	14	21	30	52
Immersed	Control	0.00	1.01	2.33	1.66	2.47	3.89
	Epoxy	0.00	0.43	0.64	0.48	0.33	0.63
	MMA	0.00	0.07	0.25	0.20	0.22	0.34
	Urethane	0.00	0.00	0.12	0.13	0.21	0.22
Tide	Control	0.00		1.73	3.40	3.77	6.16
	Epoxy	0.00		0.87	1.55	1.68	3.21
	MMA	0.00		0.02	0.17	0.22	0.55
	Urethane	0.00		0.10	0.39	0.38	1.56
Wall	Control	0.00	3.96	5.01	4.76	5.76	7.90
	Epoxy	0.00	0.94	0.53	0.52	0.62	0.77
	MMA	0.00	0.00	0.10	0.15	0.23	0.27
	Urethane	0.00	0.01	0.12	0.34	0.33	0.25
Horizontal	Control	0.00	1.62	4.06	3.65	4.08	6.87
	Epoxy	0.00	0.21	0.02	0.16	0.17	0.20
	MMA	0.00	0.12	0.01	0.07	0.08	0.20
	Urethane	0.00	0.00	0.04	0.08	0.13	0.19

TABLE 5 Chloride Content Measurements at 3.8-cm Depth

Depth = 3.8 cm		Average Gain in Chloride Concentration [kg/m <sup>3</sup> ]					
Exposure	Coating	Number of One-Week Exposure Cycles					
		0	7	14	21	30	52
Immersed	Control	0.00	0.06	0.58	0.24	0.82	1.57
	Epoxy	0.00	0.04	0.12	0.08	0.11	0.22
	MMA	0.00	0.02	0.12	0.07	0.05	0.14
	Urethane	0.00	0.00	0.06	0.08	0.12	0.19
Tide	Control	0.00		0.19	1.06	1.08	3.69
	Epoxy	0.00		0.10	0.35	0.36	1.19
	MMA	0.00		0.13	0.07	0.07	0.12
	Urethane	0.00		0.00	0.09	0.15	0.31
Wall	Control	0.00	1.38	1.75	1.64	1.44	4.60
	Epoxy	0.00	0.13	0.10	0.10	0.11	0.35
	MMA	0.00	0.02	0.14	0.00	0.10	0.26
	Urethane	0.00	0.00	0.09	0.10	0.17	0.26
Horizontal	Control	0.00	0.15	0.72	0.75	1.14	2.38
	Epoxy	0.00	0.05	0.06	0.07	0.11	0.19
	MMA	0.00	0.03	0.13	0.03	0.07	0.19
	Urethane	0.00	0.00	0.03	0.05	0.06	0.17

A 1-year testing period was chosen to achieve a nearly steady-state diffusion rate and an almost constant surface chloride concentration. This is important for a more accurate determination of the  $k$  constant and to allow chloride concentrations to increase at the 2.5- and 3.8-cm depths to achieve a more accurate gain in chloride concentrations at these depths.

The chloride exposure conditions in the United States have been categorized as low (with a surface concentration,  $C_{\text{surface}} = 0$

to 2.4 kg/m<sup>3</sup>), moderate ( $C_{\text{surface}} = 2.4$  to 4.8 kg/m<sup>3</sup>), high ( $C_{\text{surface}} = 4.8$  to 5.9 kg/m<sup>3</sup>), and severe ( $C_{\text{surface}} = 5.9$  to 8.9 kg/m<sup>3</sup>) (8). The effective  $D_c$ 's within each of these four chloride exposure conditions are 0.32, 0.58, and 0.84 cm<sup>2</sup>/year (8).

In the analysis, 50 years of corrosion protection was selected as the maximum corrosion protection service life. Also, the depth  $x$  was selected as 4.1 cm, which is the depth of 2.5 percent of the reinforcing steel, which is a function of the design cover of 5.1 cm with

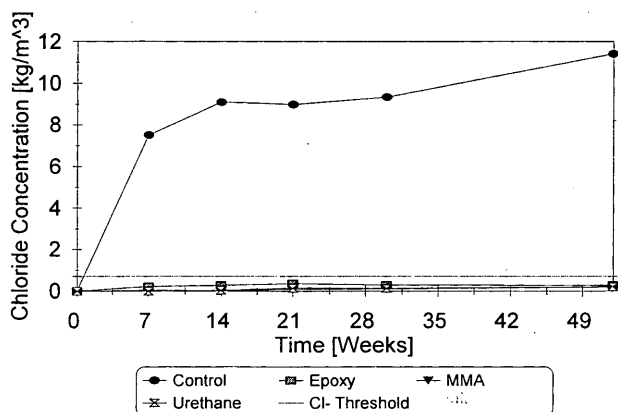


FIGURE 3 Average gain in chloride concentration, horizontal surface exposure.

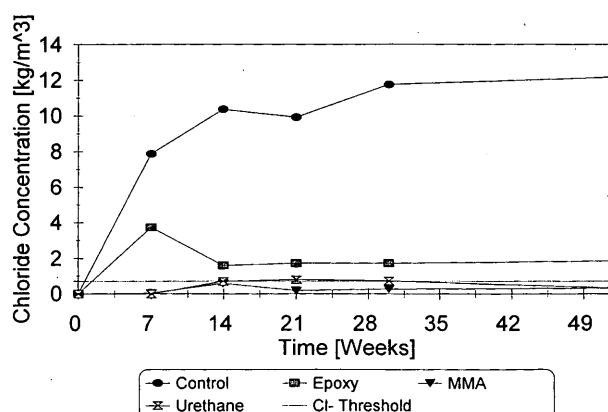


FIGURE 4 Average gain in chloride concentration, vertical surface exposure.

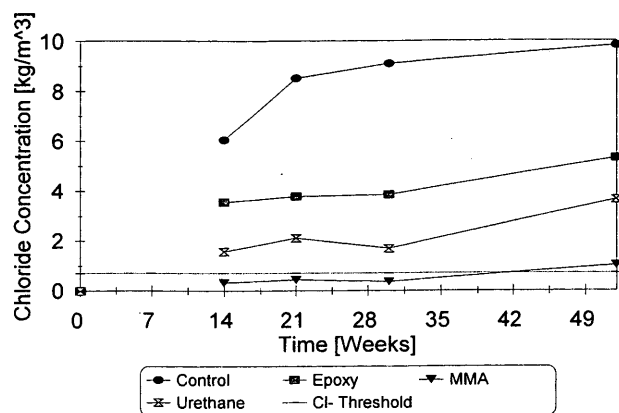


FIGURE 5 Average gain in chloride concentration, tidal zone surface exposure.

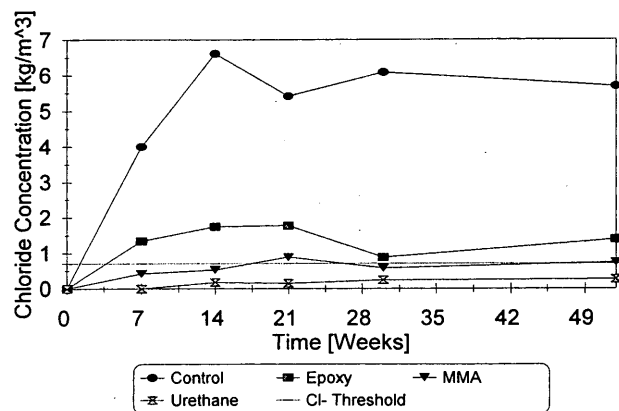


FIGURE 6 Average gain in chloride concentration, immersed zone surface exposure.

a standard deviation of 0.5 cm. The chloride threshold value for corrosion initiation for bare steel is  $C_{(x,t)}$  of 0.71 kg/m<sup>3</sup>. For the desired  $t$  of 50 years for corrosion protection and the field  $C_{\text{surface}}$  of 2.4 kg/m<sup>3</sup>, for low chloride exposure condition, the corresponding  $k$ -value,  $k_{\text{field}}$ , is 0.339 kg/(m<sup>3</sup> · year<sup>0.5</sup>), which was calculated from the following equation:

$$C_{\text{surface}} = k_{\text{field}} \sqrt{t} \quad (2)$$

$$2.4 = k_{\text{field}} \sqrt{50} \Rightarrow k_{\text{field}} = 0.339 \quad (3)$$

For low, moderate, high, and severe exposure conditions  $k_{\text{field}}$  values are 0.339, 0.679, 0.834, and 1.26 kg/(m<sup>3</sup> · year<sup>0.5</sup>), respectively. To determine the field time equivalent  $t_{\text{eq}}$  for the tested coatings it is necessary to use field diffusion constant and chloride concentration at depth  $x$  and a modified  $k$  coefficient:

$$k_{\text{modified}} = (k_{\text{coating}}/k_{\text{control}}) \cdot k_{\text{field}}$$

For the severest exposure condition ( $D_c = 0.84$  cm<sup>2</sup>/year,  $C_0 = 8.9$  kg/m<sup>3</sup>, and the epoxy coating in the immersed zone exposure condition) the modified  $k$  coefficient is.

$$k_{\text{modified}} = (k_{\text{coating}}/k_{\text{control}}) \cdot k_{\text{field}} = (1.928/7.829) \cdot 1.26 = 0.31 \text{ kg/(m}^3 \cdot \text{year}^{0.5})$$

The corrosion protection time  $t_{\text{eq}}$  is determined by an interactive solution to Equation 1, as shown in Equation 4:

$$0.71 = 0.31 \sqrt{t_{\text{eq}}} \left[ e^{-4.1^2/(4 \cdot 0.84 t_{\text{eq}})} - \frac{4.1 \sqrt{\pi}}{2 \sqrt{(0.84 t_{\text{eq}})}} \left( 1 - \text{erf} \frac{4.1}{2 \sqrt{(0.84 t_{\text{eq}})}} \right) \right] \quad (4)$$

The time equivalent for the epoxy coating in the immersed zone exposure condition is equal to 29 years. Tables 7, 8, and 9 present calculated equivalent times for the three coatings and the control that correspond to all exposure conditions occurring in the United States. Note that the protection times presented for the control section (no coating) agree with field observations and thus validate the presented methodology.

If the service life (equivalent time) exceeded 50 years then 50 years was recorded as the maximum service life. One must remember that these values are based on the diffusion properties of particular coatings. Other factors, such as resistance to ultraviolet light or mechanical or other characteristics may be contributing to a much faster rate of coating degradation.

The methodology presented here is a rational approach to estimating the corrosion protection service lives of various coatings based on chloride diffusion through the coating. It recognizes and accounts for the fact that coatings do not or will not exclude all chloride. However, field studies are needed to determine if and what exposure conditions other than chloride diffusion would limit the corrosion protection service lives of concrete coatings.

TABLE 6 Regression Analysis Results:  $k$  Coefficients [kg/(m<sup>3</sup> year<sup>0.5</sup>)]

Exposure Condition	Coating Type			
	Control	Epoxy	MMA	Urethane
Horizontal	13.303	0.375	0.164	0.175
Vertical (Wall)	14.932	2.713	0.421	0.740
Immersed	7.829	1.928	0.944	0.273
Tide	11.241	5.564	0.772	3.153

**TABLE 7 Time Equivalent for Field Conditions and Diffusion Constant of 0.32 cm<sup>2</sup>/year**

Field Surface Concentration [kg/m <sup>3</sup> ]	Exposure Condition	Time Equivalent [years]			
		Control	Epoxy	MMA	Urethane
8.9	Horizontal	18	50	50	50
	Wall	18	50	50	50
	Immersed	18	47	50	50
	Tide	18	27	50	42
5.9	Horizontal	22	50	50	50
	Wall	22	50	50	50
	Immersed	22	50	50	50
	Tide	22	37	50	50
4.8	Horizontal	26	50	50	50
	Wall	26	50	50	50
	Immersed	26	50	50	50
	Tide	26	44	50	50
2.4	Horizontal	44	50	50	50
	Wall	44	50	50	50
	Immersed	44	50	50	50
	Tide	44	50	50	50

**TABLE 8 Time Equivalent for Field Conditions and Diffusion Constant of 0.58 cm<sup>2</sup>/year**

Field Surface Concentration [kg/m <sup>3</sup> ]	Exposure Condition	Time Equivalent [years]			
		Control	Epoxy	MMA	Urethane
8.9	Horizontal	12	50	50	50
	Wall	12	47	50	50
	Immersed	12	34	50	50
	Tide	12	19	50	30
5.9	Horizontal	15	50	50	50
	Wall	15	50	50	50
	Immersed	15	50	50	50
	Tide	15	26	50	46
4.8	Horizontal	18	50	50	50
	Wall	18	50	50	50
	Immersed	18	50	50	50
	Tide	18	32	50	50
2.4	Horizontal	32	50	50	50
	Wall	32	50	50	50
	Immersed	32	50	50	50
	Tide	32	50	50	50

TABLE 9 Time Equivalent for Field Conditions and Diffusion Constant of 0.84 cm<sup>2</sup>/year

Field Surface Concentration [kg/m <sup>3</sup> ]	Exposure Condition	Time Equivalent [years]			
		Control	Epoxy	MMA	Urethane
8.9	Horizontal	9	50	50	50
	Wall	9	40	50	50
	Immersed	9	29	50	50
	Tide	9	15	50	25
5.9	Horizontal	12	50	50	50
	Wall	12	50	50	50
	Immersed	12	45	50	50
	Tide	12	22	50	39
4.8	Horizontal	14	50	50	50
	Wall	14	50	50	50
	Immersed	14	50	50	50
	Tide	14	26	50	49
2.4	Horizontal	26	50	50	50
	Wall	26	50	50	50
	Immersed	26	50	50	50
	Tide	26	50	50	50

## REFERENCES

1. *Our Nation's Highways. Selected Facts and Figures*. Publication FHWA-PL-90-024. FHWA, U.S. Department of Transportation, undated, p. 11.
2. *A Federal Surface Transportation Program for the Future*. (American Road & Transportation Builders Association, undated, p. 8.
3. Bennett, J. Corrosion of Reinforcing Steel in Concrete and Its Prevention by Cathodic Protection. *Anti-Corrosion Methods and Materials*, Vol. 33, No. 11, Oct. 1986, pp. 12-15, 17.
4. Pfeifer, D. W., and M. J. Scali. *NCHRP Report 244: Concrete Sealers for Protection of Bridge Structures*. TRB, National Research Council, Washington, D.C., Dec. 1981.
5. Wohl, R. L., and R. W. LaFraugh. Criteria for the Selection of Penetrating Hydrophobic Sealers Used in the Repair of Concrete Parking Decks. In *Building Deck Waterproofing*, ASTM STP 1084 (L. E. Gish, ed.), American Society for Testing and Materials, Philadelphia, 1990, pp. 75-82.
6. Ashmore, W. F. Coating Concrete in Industrial Facilities. *Journal of Protective Coatings & Linings*, Nov. 1986, pp. 48-54.
7. Crank, J. *Mathematics of Diffusion*. The University Press, Oxford, U.K., 1970.
8. Weyers, R. E., B. D. Prowell, M. M. Sprinkel, and M. Vorster. *Concrete Bridge Protection, Repair, and Rehabilitation Relative to Reinforcement Corrosion: A Methods Application Manual*. Report SHRP-S-360. Strategic Highway Research Program, National Research Council, Washington, D.C., 1993.

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