EFFECTS OF INITIAL SURFACE TREATMENT TIMING ON CHLORIDE CONCENTRATIONS IN CONCRETE BRIDGE DECKS

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ABSTRACT

In consideration of concrete cover thickness and the presence of stay-in-place metal forms (SIPMFs), the objective of this research was to determine the latest timing of initial surface treatment applications on concrete bridge decks subjected to external chloride loading before chlorides accumulate in sufficient quantities to initiation corrosion of the reinforcing steel. Chloride concentration data for this research were collected from 12 concrete bridge decks located within the Interstate 215 corridor in Salt Lake City, Utah. Numerical modeling was utilized to generate a chloride loading function and to determine the diffusion coefficient of each deck. Based on average diffusion coefficients for decks with and without SIPMFs, chloride concentration profiles were computed through time for cover thicknesses of 2.0 in. (50.8 mm), 2.5 in. (63.5 mm), and 3.0 in. (76.2 mm).

The results of the work show that the average diffusion coefficient for bridge decks with SIPMFs is approximately twice that of decks without SIPMFs and that, on average, each additional 0.5 in. (12.7 mm) of cover beyond 2.0 in. (50.8 mm) allows an extra 2 years for decks with SIPMFs and 5 years for decks without SIPMFs before a surface treatment must be placed to prevent excessive accumulation of chlorides. Although the data generated in this research are based on conditions typical of bridge decks in Utah, they clearly illustrate the effect of cover depth and the presence of SIPMFs. This information may be especially valuable to bridge engineers and managers responsible for programming surface treatments on concrete bridge decks.

INTRODUCTION

Chloride penetration into concrete bridge decks is a leading cause of corrosion of reinforcing steel and can lead to rapid deterioration of affected structures (*1*). This problem is especially paramount in areas where chlorides are prevalent, such as coastal regions and cold regions where deicing salts are used as part of winter roadway maintenance. Unfortunately, exposure of decks to high chloride concentrations in these areas is generally unavoidable, either because the chlorides are present in the environment or because they play an important role in road safety.

A solution many departments of transportation (DOTs) have utilized is the placement of impermeable surface treatments on concrete bridge decks as barriers against chloride ingress (*2*). However, DOTs vary widely in their policies about when surface treatments should be applied and achieve diverse performance results (*3*). Although surface treatments should be applied to decks before chlorides accumulate in sufficient quantities to initiate corrosion, the proper timing of surface treatment placement depends upon the salt loading, the concrete cover thickness, and the diffusion coefficient of the concrete with which the deck is constructed (*4*). Guidelines incorporating these factors are needed to maximize the efficacy of surface treatments and thus minimize life-cycle costs of bridge decks.

While previous researchers have compared the relative utility of different types of surface treatments, proposed methods of computing diffusion coefficients for bridge decks, and investigated the effects of surface treatments on diffusion coefficients (*1, 5, 6, 7*), the literature is generally absent of publications addressing the proper timing of surface treatment placement with respect to chloride ingress. Furthermore, published research studies concerning applications of surface treatments and their effects on chloride diffusion are based largely on laboratory specimens rather than on actual bridge decks (*2, 5, 7, 8, 9, 10*) and do not account for the presence of stay-in-place metal forms (SIPMFs), for example, that have been shown to increase rates of chloride ingress in the field (*11*).

Therefore, in consideration of concrete cover thickness and the presence of SIPMFs, the specific objective of this research was to determine the latest timing of initial surface treatment applications on concrete bridge decks subjected to external chloride loading before chlorides accumulate in sufficient quantities to initiate corrosion, present or future, during the service life of the deck. (Once applied, the surface treatments are assumed to be renewed or replaced as needed to maintain a constant barrier to chlorides through time.) The following sections discuss the effects of certain deck properties on chloride diffusion, explain the procedures associated with this research, present the field and laboratory test results, discuss the numerical modeling performed, and offer conclusions about the timing of surface treatment placements on bridge decks with and without SIPMFs.

CHLORIDE DIFFUSION

Chlorides penetrate concrete bridge decks through the process of diffusion and can initiate corrosion of steel reinforcement at a threshold concentration commonly assumed to be 2.0 lb of chloride per cubic yard of concrete (1.2 kg of chloride per cubic meter of concrete) (*12*). Because concrete is relatively weak in tension, the formation of rust, which is approximately 200% to 600% greater in volume than the parent materials (*11*), leads to cracking and delamination of the concrete deck. The formation of distress in the deck can then reduce the structural integrity and ride quality of the deck.

The rate at which chlorides can diffuse into concrete depends upon the presence and continuity of pore water within the concrete matrix (*1*). The properties of the concrete pore

structure are determined to a large degree by the water-cementitious material ratio, degree of hydration, and porosity of the concrete. For a given concrete mixture, the external chloride loading and cover thickness then govern the time required for chlorides to accumulate in critical concentrations in the vicinity of the reinforcing steel.

Adding a surface treatment to the concrete surface is an effective and economical method of disrupting the ingress of chlorides (*2*). Common surface treatment application types for concrete bridge decks include epoxy, epoxy-urethane, methacrylate, and silane (*3*). Although the chemical compositions of these products vary, the products are usually intended to serve as barriers to the ingress of both moisture and chlorides. A national questionnaire survey of state DOTs performed in 2004 indicated that 14 of 20 respondents specifically utilize surface treatments for this purpose. However, the timing of initial surface treatment applications varies widely, ranging from 1 year to 25 years from the date of deck construction, with similar variability in the frequency of repeated applications (*3*). The findings of this survey demonstrate the need for further research on this topic.

The presence of certain construction features, such as SIPMFs, can also affect rates of chloride ingress in concrete bridge decks by restricting evaporation of moisture from the deck and therefore causing higher average moisture contents associated with higher effective diffusion rates (*11*). The equilibrium moisture content achieved by concrete bridge decks depends on climatic variables such as temperature, relative humidity, and amount of precipitation. All of these variables were considered directly or indirectly in this research.

PROCEDURES

Field data collection, laboratory data analysis, and numerical modeling were performed to meet the objectives of this research. In cooperation with the Utah Department of Transportation (UDOT), research personnel at Brigham Young University (BYU) collected chloride concentration data during the summer of 2005 from 12 concrete bridge decks all located within the Interstate 215 (I-215) corridor in Salt Lake City, Utah. UDOT bridge engineers selected six concrete bridge decks with SIPMFs and six without SIPMFs for evaluation in this project. As displayed in Table 1, all of the bridge decks ranged from 16 to 21 years in age at the time of testing. Because of their close geographic proximity and their similar highway class, all of the decks were subject to similar traffic loading, climatic conditions, and maintenance treatments, including the applications of deicing salts during winter months. Details of the experimental methodology are given in the following sections.

Field Testing

On each bridge deck, six 6-ft by 6-ft (1.83-m by 1.83-m) test locations were randomly distributed within the single lane closed for testing. The number of test locations required per deck was determined using statistics based on the spatial variability in chloride concentrations associated with the results of previous work at BYU (*13*), and randomizing the test locations within each lane was necessary to ensure that every possible test location had an equal chance of being selected.

Sample extractions for chloride testing were performed in one location within each test area. Each extraction was accomplished in approximately 1-in. (25.4-mm) lifts using four different hammer drill bits that ranged in diameter from 0.75 in. (19.05 mm) to 1.5 in. (38.1 mm). On bridge decks with SIPMFs, seven or eight lifts were extracted, depending on the thickness of the bridge deck. However, on decks without SIPMFs, only seven lifts were

collected; the researchers avoided drilling through the bottom of the concrete decks to facilitate patching of the test holes. The drill bit diameter was decreased 0.25 in. (6.35 mm) after every two lifts to minimize contamination that may have otherwise occurred in deeper samples through inadvertent scraping of the sides of the hole nearer the surface during the drilling process. After each lift was pulverized, the concrete sample was removed from the hole and placed into a plastic bag. The hole, drill bit, and scoop used for sample collection were then cleaned using compressed air. The depth of the lift was measured using a digital micrometer to enable preparation of chloride concentration profiles. The drilling process was then repeated until extraction of the seven or eight lifts was completed.

Laboratory Testing

The pulverized concrete samples collected from each deck were transported to the BYU Highway Materials Laboratory for chloride concentration testing following American Society for Testing and Materials C 1218, Standard Test Method for Water Soluble Chloride in Mortar and Concrete. This test requires boiling of 0.35-oz (10-g) samples in water for 5 minutes and a subsequent 24-hour cooling period. After cooling, the solution is filtered and treated with equal amounts of nitric acid and hydrogen peroxide. In this research, the chloride concentration of the solution was then measured using a laboratory chloride-ion-selective probe. Given the volume of the solution and the original mass of the pulverized concrete sample, researchers converted the measured chloride concentrations from units of mg/mL to lb of chloride per cubic yard of concrete, assuming a concrete density of 145 lb/ft^3 (2320 kg/m^3). Then, given a porosity and degree of saturation, researchers computed chloride concentrations in units of moles of chloride per liter of pore water solution for use in numerical modeling. Based on the concrete mixture design presented in Table 2, which according to UDOT personnel is typical of all of the decks evaluated in this study, the porosity of the concrete was estimated to be 18% for all of the decks. The degrees of saturation for decks with and without SIPMFs were estimated from information in the literature to be 92.5% and 85.0%, respectively (*14*).

Numerical Modeling

To facilitate analysis of chloride concentration profiles, the midpoint of each depth interval was computed, and chloride concentrations at 1-in. (25.4-mm) depth intervals were then determined for each test location by interpolation. The average chloride concentration associated with each depth interval was also computed for each deck for use in determining diffusion coefficients.

Diffusion coefficients, which were assumed to be constant through time, were calculated from the measured chloride profiles using a computer program developed at the National Institute of Standards and Technology (NIST) (*15*). The program simulates one-dimensional chloride diffusion in concrete and accounts for the effects of water-cementitious material ratio, degree of hydration, and porosity. It also allows for variable external chloride loading, an open or closed upper boundary, and an open or reflecting lower boundary. With these options, the model can be effectively used to simulate the effects of both surface treatments and SIPMFs on chloride diffusion in concrete bridge decks.

Inputs for the numerical modeling were determined from local climatic conditions, field measurements, a volumetric analysis of the concrete mixture design typically specified by UDOT for construction of bridge decks, and information published in the literature (*16, 17*). Specifically, the beginning month of exposure, member thickness, water-cementitious material ratio, degree of hydration, volume fraction of aggregate, air content, initial chloride

concentration of concrete, and thickness of surface layer were uniquely determined for this modeling, while default values provided by the program were used for all of the other variables. All of the input variables held constant for each bridge deck are presented in Table 3. (Because the program utilizes metric units, data associated with the program operation are presented only in metric units.)

The total duration of exposure to chlorides was specified separately for each individual deck based on its age, where surface concentrations were determined on a monthly basis and assumed to remain consistent from year to year. The form of the function used to represent surface chloride concentrations followed that established in previous research (*18*), and the values of the coefficients in the equation were selected through an optimization process performed in this research to provide the best matches overall between measured and simulated chloride concentration profiles for both types of bridge decks. To simulate chloride penetration in decks with SIPMFs, a reflecting lower boundary condition was utilized; otherwise, an open condition was specified for both boundary conditions in the numerical modeling, equating to constant exposure of the deck surface to chlorides and a constant zero-valued chloride concentration at the bottom of the deck.

After all of the other parameters were set, diffusion coefficients were varied in a systematic trial-and-error procedure to achieve the best possible matches between measured and simulated chloride concentration profiles, where trial simulations were evaluated based on the sum of the squared differences between the measured and simulated profiles at 1-in. (25.4 mm) depth intervals. In each simulation, the program results in units of moles of chloride per liter of pore water solution were directly compared with the measured values. The diffusion coefficient associated with the minimum sum of the squared differences was selected for the given deck in each case. One diffusion coefficient per deck was computed, and average diffusion coefficients for decks with and without SIPMFs were then calculated.

Following these computations, the effects of surface treatment application at different deck ages were simulated using the NIST computer program. When a surface treatment was applied, the upper boundary condition was programmed to automatically close on the date of treatment application, effectively simulating the assumed condition of a completely sealed deck surface. After the upper boundary condition was closed, no further chloride ingress was permitted, and the program then simulated the redistribution of chlorides already in the deck through a duration of time beginning on the date of surface treatment application and ending at a deck age of 30 years. In the numerical modeling, bridge decks were assumed to be protected from chloride ingress from the time the first treatment was applied through the end of the simulation at a deck age of 30 years. The effects of surface treatment placement 1 to 15 years after deck construction were investigated in this manner for cover thicknesses of 2.0 in. (50.8 mm), 2.5 in. (63.5 mm), and 3.0 in. (76.2 mm). The chloride profiles resulting from this modeling were then used to produce graphs presenting the effect of surface treatment placement on chloride concentrations at the depth of the deck reinforcement during the 30-year period. For plotting, the program results in units of moles of chloride per liter of pore water solution were converted to lb of chloride per cubic yard of concrete using the same estimations of concrete density, porosity, and degrees of saturation given earlier. The values were then compared to the accepted threshold value of 2.0 lb of chloride per cubic yard of concrete (1.2 kg of chloride per cubic meter of concrete) to identify the recommended surface treatment timing.

RESULTS

The results of this research include both measured and simulated chloride concentrations. The results of the field testing are given in Table 4, which displays the average chloride concentrations and associated standard deviations at 1-in. (25.4-mm) depth intervals for each deck. As shown in Table 1, the average age of the decks with SIPMFs was 3 years less than that of the decks without SIPMFs; therefore, the decks with SIPMFs probably experienced less total salt application than those without SIPMFs by the time of testing. To compare the chloride concentrations between decks with and without SIPMFs and properly account for differences in age, researchers performed an analysis of covariance (ANOCOVA). In the ANOCOVA, data obtained from decks with and without SIPMFs were treated as samples from two different populations. The null hypothesis in the test was that the chloride concentrations from decks with and without SIPMFs were equal, while the alternative hypothesis was the postulation that the chloride concentrations were different. In the analyses, *p*-values of less than 0.03 were obtained for all tested depths except 1 in. and 7 in. (177.8 mm); the *p*-values for those tests exceeded 0.10. (A test associated with a depth of 8 in. (203.2 mm) could not be performed because of the absence of data from that depth among decks without SIPMFs.) Therefore, applying the standard 0.05 level of significance to the test results, one may conclude that the chloride concentrations in the middle 5 in. (152.4 mm) of the decks are significantly different, thus warranting separate consideration of decks with and without SIPMFs.

The function selected to represent the surface chloride exposure of the decks in the numerical modeling is represented by Equation 1:

$$C = 3.38 + 1.07 \cdot \cos\left(\frac{\pi \cdot t}{6}\right) \tag{1}$$

where C = chloride concentration of pore water for month t, mol/L
t = month of year from 1 to 12 to represent January to December, respectively

Based on this function, the calculated diffusion coefficients for each deck are shown in Table 5. The average diffusion coefficient for bridge decks with SIPMFs is approximately twice that of decks without SIPMFs; as explained previously, the presence of SIPMFs reduces the deck surface area from which water can evaporate, leading to higher degrees of saturation and therefore greater pore water continuity that permits more rapid diffusion of chlorides into the concrete (*8*).

Chloride concentrations resulting from computer simulations are shown in Figures 1 to 6 for a 30-year period of deck life, where Figures 1 to 3 represent decks with SIPMFs and Figures 4 to 6 represent decks without SIPMFs. For each type of deck, these figures show the chloride concentrations at different cover depths as they vary with time and surface treatment application timing. Ideally, surface treatments should be placed sufficiently early in the deck life that the chloride concentrations never exceed 2 lb of chloride per cubic yard of concrete (1.2 kg of chloride per cubic meter of concrete) at the level of the reinforcing steel. Even though the chloride concentration at the level of the reinforcement may be less than this threshold value at the time of surface treatment application, the chloride concentration may increase above the threshold value with time as the chlorides nearer the surface diffuse downward into the deck toward a condition of equilibrium. For this reason, the chloride concentration at the level of the

steel and the chloride concentration gradient in the concrete cover should both be considered by bridge engineers and managers responsible for programming surface treatment placements.

Based on the figures, the latest timing of initial surface treatment application for each combination of deck type and cover thickness was determined by locating the year of surface treatment application nearest, but still below, the threshold value of 2 lb of chloride per cubic yard of concrete (1.2 kg of chloride per cubic meter of concrete). This selection ensured that the bridge deck would never experience corrosion as long as the surface treatment was maintained or replaced throughout the remainder of the deck service life. Table 6 summarizes the recommended deck ages by which surface treatments should be placed. Although the data are based on concrete mixture properties and external chloride loading typical of bridge decks in Utah, they clearly illustrate the effect of cover depth and the presence of SIPMFs. Greater cover depths allow longer delays in surface treatment placements following deck construction; on average, each additional 0.5 in. (12.7 mm) of cover beyond 2.0 in. (50.8 mm) allows an extra 2 years for decks with SIPMFs and 5 years for decks without SIPMFs before a surface treatment must be placed to prevent future accumulation of chlorides in concentrations above the threshold value. Because of their reduced diffusion coefficients compared to decks with SIPMFs, decks without SIPMFs may be programmed for surface treatment application approximately three times later than those with SIPMFs.

CONCLUSION

Recognizing the need to minimize life-cycle bridge costs, bridge engineers and managers in coastal areas and cold regions frequently specify the application of surface treatments on concrete bridge decks as barriers against chloride ingress. In consideration of concrete cover thickness and the presence of SIPMFs, the objective of this research was to determine the latest timing of initial surface treatment applications before chlorides accumulate in sufficient quantities to initiate corrosion during the service life of the deck. Chloride concentration data for this research were collected from 12 concrete bridge decks located within the I-215 corridor in Salt Lake City, Utah. All bridge decks ranged from 16 to 21 years in age, and six of the decks were constructed using SIPMFs. Numerical modeling was utilized to generate a chloride loading function typical of the tested decks and to determine the diffusion coefficient of each deck. Based on average diffusion coefficients for decks with and without SIPMFs, chloride concentration profiles were computed through time for cover thicknesses of 2.0 in (50.8 mm), 2.5 in. (63.5 mm), and 3.0 in. (76.2 mm).

The results of the work show that the average diffusion coefficient for bridge decks with SIPMFs is approximately twice that of decks without SIPMFs and that, on average, each additional 0.5 in. (12.7 mm) of cover beyond 2.0 in. (50.8 mm) allows an extra 2 years for decks with SIPMFs and 5 years for decks without SIPMFs before a surface treatment must be placed to prevent future accumulation of chlorides in concentrations above the threshold value of 2 lb of chloride per cubic yard of concrete (1.2 kg of chloride per cubic meter of concrete). Because of their reduced diffusion coefficients compared to decks with SIPMFs, decks without SIPMFs may be scheduled for surface treatment application approximately three times later than those with SIPMFs. Although the data generated in this research are based on concrete mixture properties and external chloride loading typical of bridge decks in Utah, they clearly illustrate the effect of cover depth and the presence of SIPMFs. This information may be especially valuable to bridge engineers and managers responsible for programming surface treatments on concrete bridge decks.

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6. Simulated chloride concentrations of decks without SIPMFs at a 3.0-in. (76.2-mm) cover depth.

TABLE 1 Deck Ages at Time of Testing

Deck ID	Age (yr)
Decks with SIPMFs	
1	18
2	18
3	18
4	17
5	16
6	16
Average	17
Decks without SIPMFs	
7	21
8	18
9	17
10	21
11	21
12	20
Average	20

TABLE 2 Concrete Mixture Design

Ingredient	Weight lb (kg)	Specific Gravity	Volume yd^3 (m^3)
Coarse Aggregate (SSD)	1714 (777)	2.55	0.399 (0.305)
Fine Aggregate (SSD)	1071 (486)	2.60	0.244 (0.187)
Cement	519 (235)	3.15	0.098 (0.075)
Fly Ash	115 (52)	2.30	0.030 (0.023)
Free Water	280 (127)	1.00	0.166 (0.127)
Water Reducer	1.19 (0.54)	1.00	0.0007 (0.0005)
Air	-	-	0.063 (0.048)

TABLE 3 Computer Program Input Values

Property	Value
Beginning Month of Exposure	October
Member Thickness (m)	0.203
Water-Cementitious Material Ratio, w/cm	0.44
Degree of Hydration	0.8
Volume Fraction of Aggregate (%)	65
Air Content (%)	6
Initial Chloride Concentration of Concrete (g Chloride/g Cement)	0
Initial Diffusion Coefficient, D_i	0
Empirical Coefficient, m	0.6
Ratio of Surface-to-Bulk Diffusion Coefficients	1
Thickness of Surface Layer (mm)	0
Activation Energy for Diffusion (kJ/mol)	40
Langmuir Isotherm Alpha Constant	1.67
Langmuir Isotherm Beta Constant	4.08
Rate Constant for Binding (s^{-1})	1.00E-07
C_3A Content of Cement (%)	5
C_4AF Content of Cement (%)	5
Rate Constant for Aluminate Reactions with Chloride (s^{-1})	1.00E-08

TABLE 4 Measured Chloride Concentrations

Depth from Surface	Chloride Concentration (mol/L)											
in. (mm)	Avg.	St. Dev.	Avg.	St. Dev.	Avg.	St. Dev.	Avg.	St. Dev.	Avg.	St. Dev.	Avg.	St. Dev.
Decks with SIPMFs	Deck 1		Deck 2		Deck 3		Deck 4		Deck 5		Deck 6	
1 (25.4)	1.856	0.458	2.666	0.506	2.309	0.566	2.234	0.673	1.536	0.358	2.697	0.742
2 (50.8)	1.033	0.413	1.560	0.546	1.521	0.693	1.000	0.488	1.042	0.183	1.577	0.462
3 (76.2)	0.497	0.199	0.771	0.299	0.908	0.467	0.435	0.335	0.610	0.080	0.839	0.318
4 (101.6)	0.160	0.099	0.336	0.189	0.449	0.311	0.190	0.216	0.317	0.061	0.385	0.176
5 (127.0)	0.078	0.095	0.106	0.101	0.166	0.167	0.087	0.151	0.115	0.046	0.135	0.087
6 (152.4)	0.031	0.036	0.029	0.035	0.059	0.096	0.048	0.097	0.037	0.025	0.044	0.033
7 (177.8)	0.015	0.016	0.008	0.009	0.035	0.065	0.030	0.062	0.019	0.029	0.018	0.012
8 (203.2)	-	-	0.001	0.000	-	-	-	-	0.009	0.011	-	-
Decks without SIPMFs	Deck 7		Deck 8		Deck 9		Deck 10		Deck 11		Deck 12	
1 (25.4)	2.254	0.323	1.755	0.322	1.749	0.520	1.085	0.266	2.085	0.384	1.951	0.576
2 (50.8)	1.595	0.381	0.545	0.150	0.355	0.320	0.102	0.104	1.084	0.441	0.935	0.435
3 (76.2)	0.774	0.352	0.045	0.031	0.083	0.111	0.016	0.019	0.415	0.243	0.159	0.143
4 (101.6)	0.238	0.188	0.017	0.015	0.041	0.028	0.007	0.002	0.124	0.114	0.052	0.058
5 (127.0)	0.044	0.043	0.007	0.002	0.031	0.025	0.006	0.002	0.020	0.019	0.007	0.002
6 (152.4)	0.006	0.002	0.011	0.013	0.030	0.026	0.005	0.001	0.005	0.002	0.005	0.002
7 (177.8)	0.004	0.001	0.015	0.026	0.026	0.025	0.006	0.002	0.005	0.001	0.005	0.002
8 (203.2)	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 5 Calculated Diffusion Coefficients

Deck ID	Diffusion Coefficient (m^2/s)
Decks with SIPMFs	
1	2.05E-11
2	3.20E-11
3	3.35E-11
4	1.90E-11
5	2.05E-11
6	3.75E-11
Average	2.72E-11
St. Dev.	0.81E-11
Decks without SIPMFs	
7	2.55E-11
8	1.00E-11
9	0.91E-11
10	0.37E-11
11	1.65E-11
12	1.30E-11
Average	1.30E-11
St. Dev.	0.75E-11

TABLE 6 Recommended Latest Timing of Initial Surface Treatment Application

Cover Depth in. (mm)	Deck Age for Surface Treatment Application (yr)	
	With SIPMFs	Without SIPMFs
2.0 (50.8)	1	5
2.5 (63.5)	3	9
3.0 (76.2)	5	15

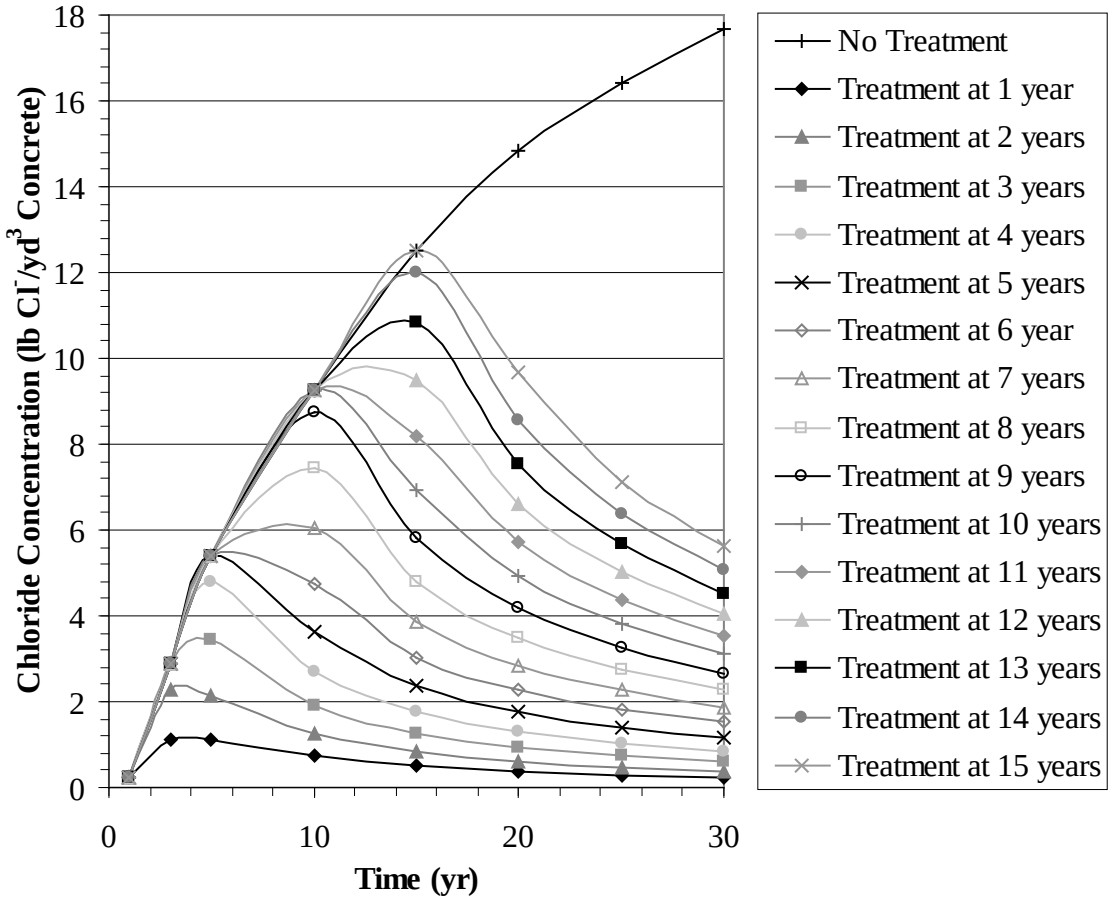

FIGURE 1 Simulated chloride concentrations of decks with SIPMFs at a 2.0-in. (50.8-mm) cover depth.

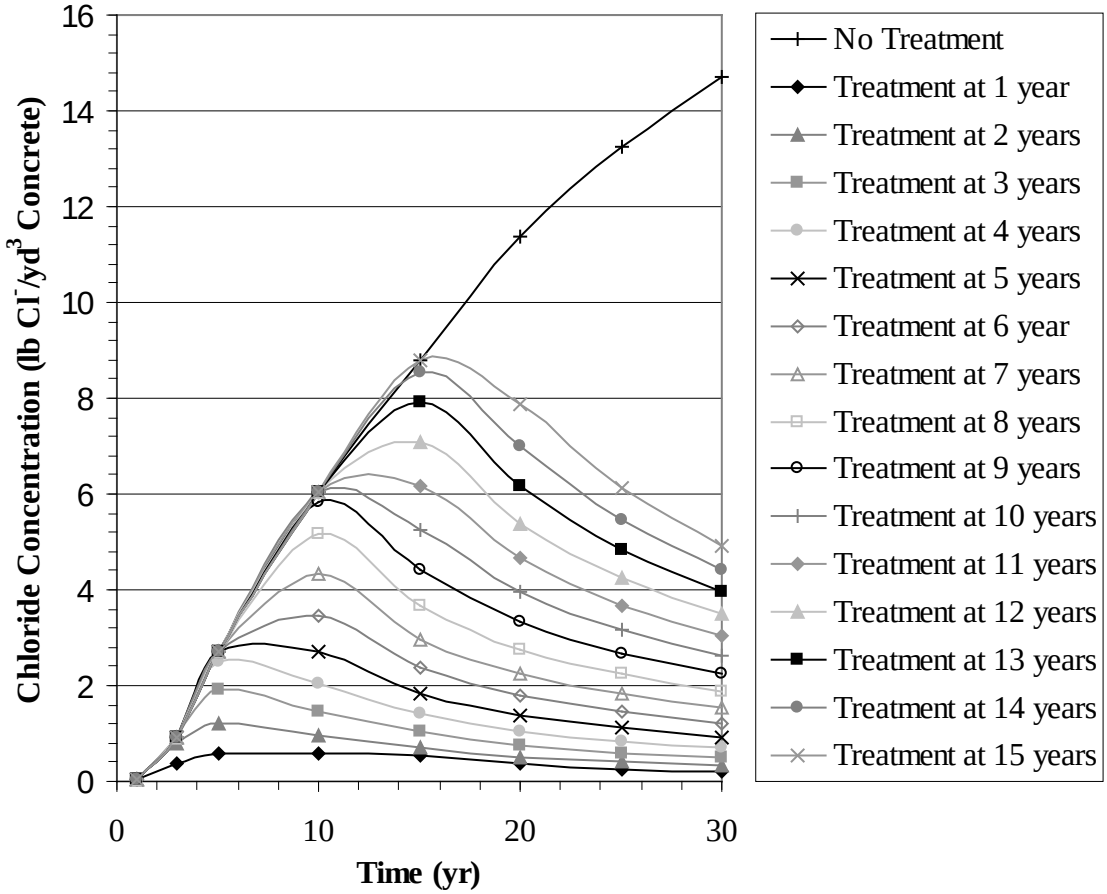

FIGURE 2 Simulated chloride concentrations of decks with SIPMFs at a 2.5-in. (63.5-mm) cover depth.

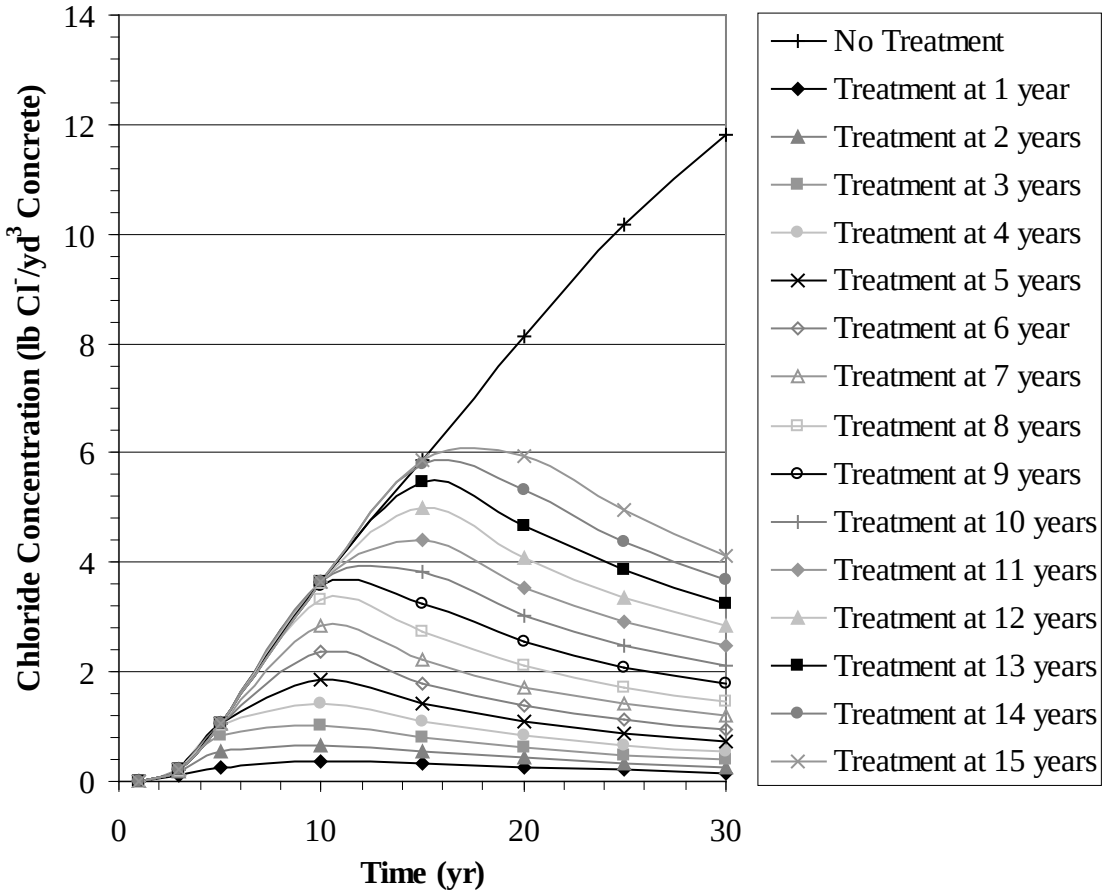

FIGURE 3 Simulated chloride concentrations of decks with SIPMFs at a 3.0-in. (76.2-mm) cover depth.

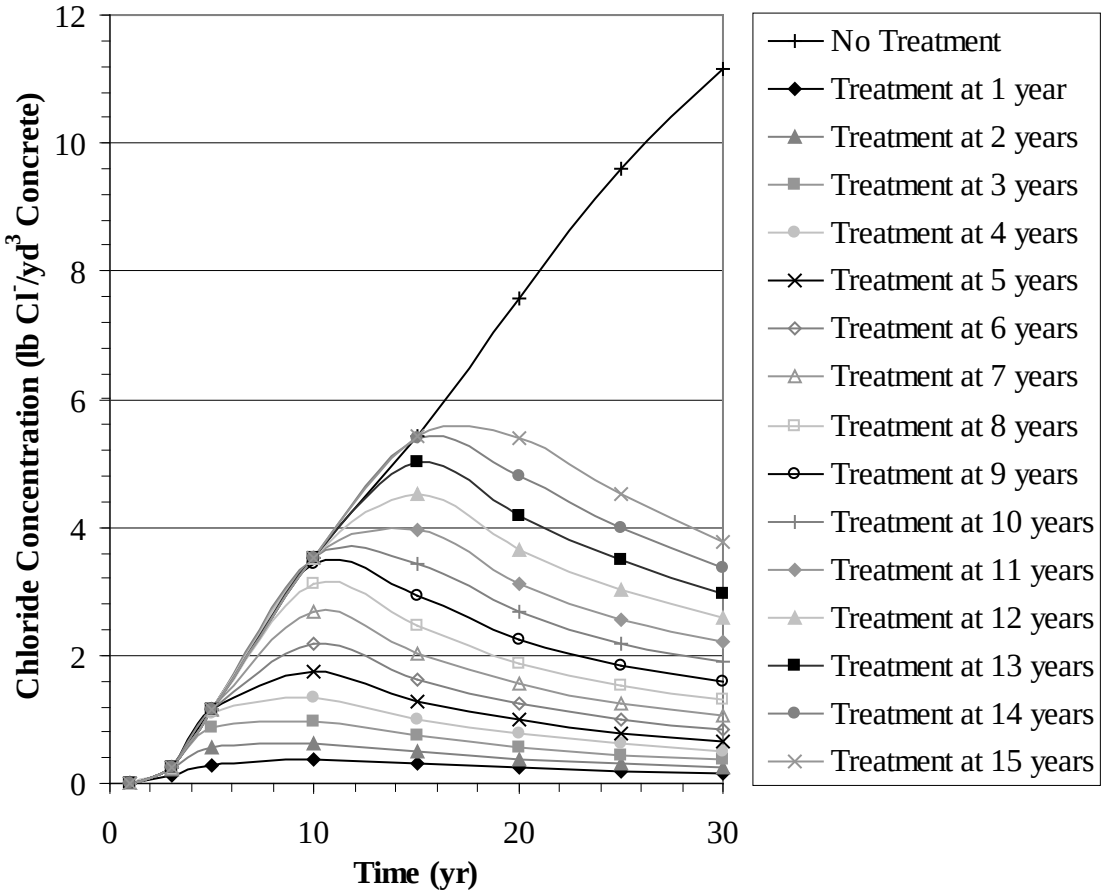

FIGURE 4 Simulated chloride concentrations of decks without SIPMFs at a 2.0-in. (50.8-mm) cover depth.

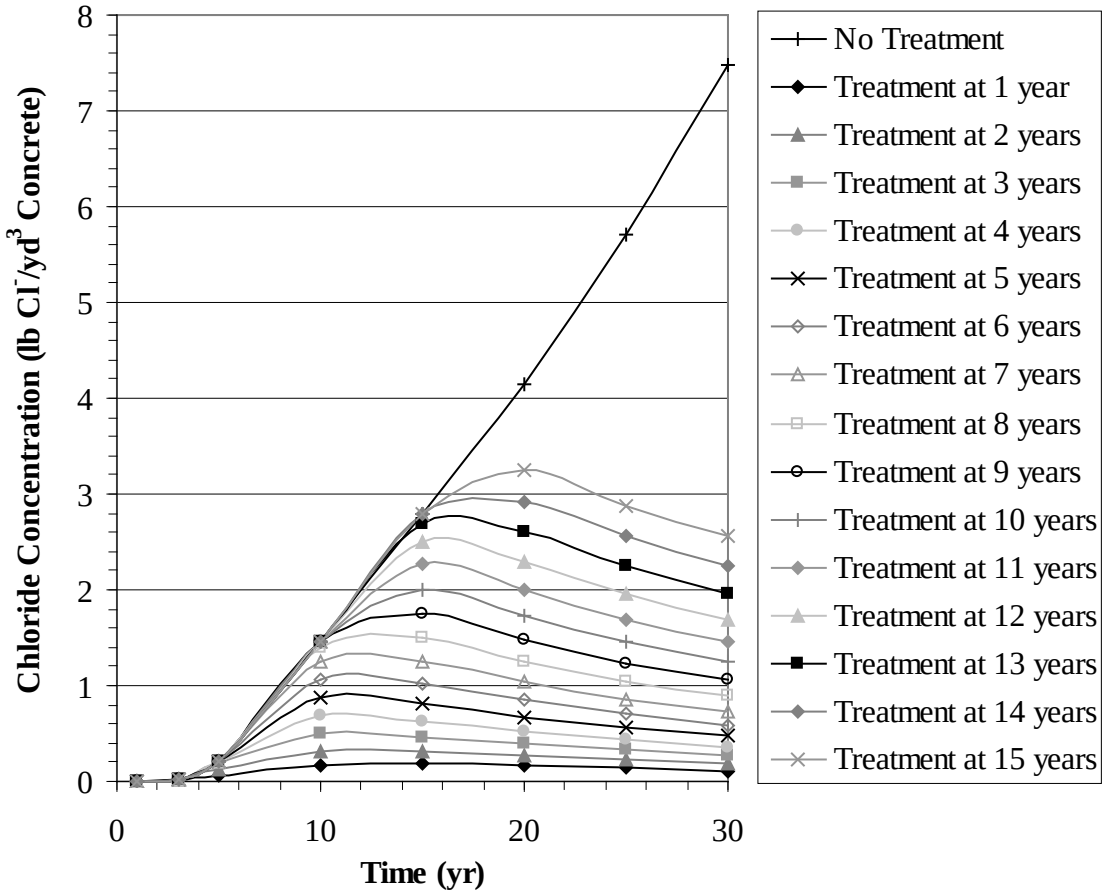

FIGURE 5 Simulated chloride concentrations of decks without SIPMFs at a 2.5-in. (63.5-mm) cover depth.

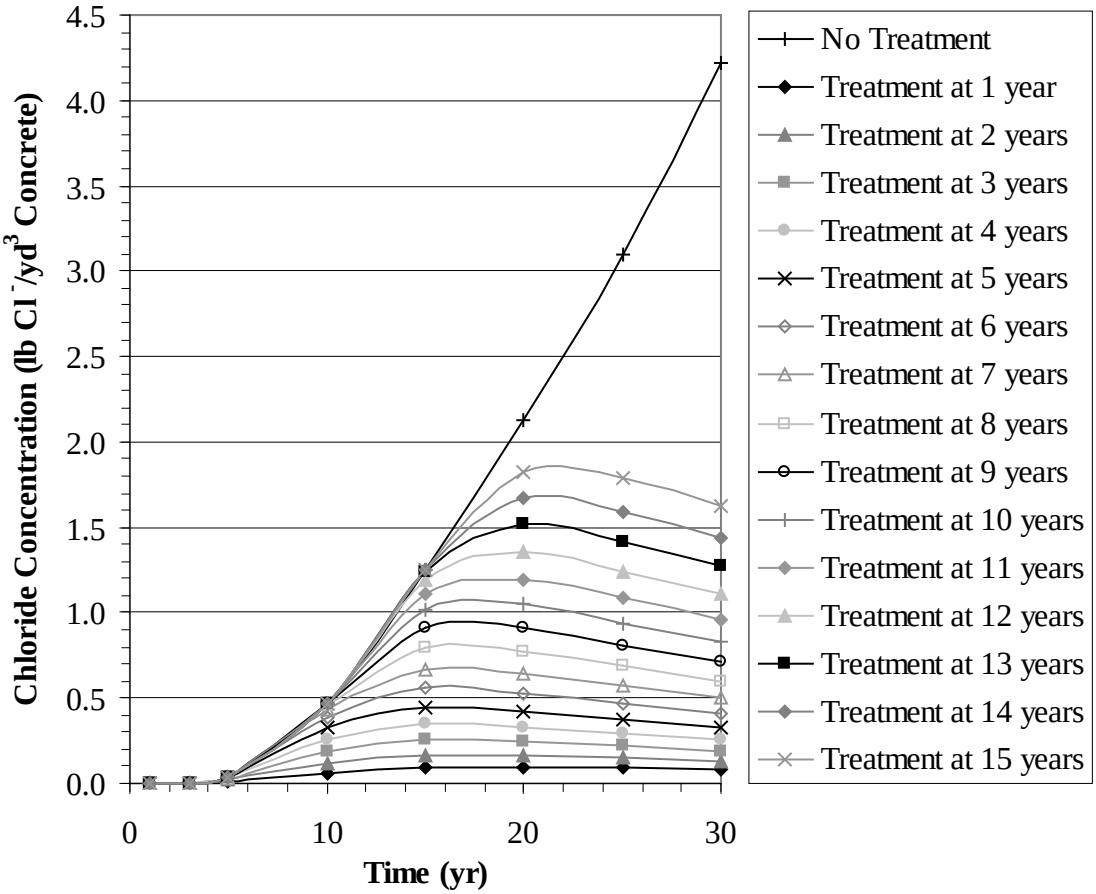

FIGURE 6 Simulated chloride concentrations of decks without SIPMFs at a 3.0-in. (76.2-mm) cover depth.