2007-01-29

Effect of Initial Surface Treatment Timing on Chloride Concentrations in Concrete Bridge Decks

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

by

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A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Civil and Environmental Engineering
Brigham Young University
April 2007

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of Aimee Worthen Birdsall in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

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

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Master of Science

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 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 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. 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., 2.5 in., and 3.0 in.

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. of cover beyond 2.0 in. 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.

Given these research findings, engineers should carefully determine the appropriate timing for initial applications of surface treatments to concrete bridge decks in consideration of cover depth and the presence of SIPMFs. For maintenance of concrete bridge decks with properties similar to those tested in this study, engineers should follow the guidelines developed in this research to minimize the ingress of chlorides into the decks over time and therefore retard the onset of reinforcement corrosion; altogether separate guidelines may be needed for decks having substantially different properties. Surface treatments should be replaced as needed to ensure continuing protection of the concrete bridge deck against chloride ingress.

ACKNOWLEDGEMENTS

The author acknowledges the help of Dr. Spencer Guthrie in planning and carrying out this project. Support for this project was provided by the Brigham Young University (BYU) Office of Research and Creative Activities and the Utah Department of Transportation (UDOT). Daniel Hsiao of UDOT is acknowledged for coordinating work between UDOT and Brigham Young University. The author also wishes to acknowledge Mike Ellis of UDOT for arranging traffic control during the bridge deck testing. BYU professors Norm Jones, Gus Williams, and Mitsuru Saito are recognized for their assistance in analyzing and editing final data. The author would like to thank Dale Bentz of the National Institute of Standards and Technology for his collaboration and advisement during the numerical modeling process. BYU students Adam Birdsall, Brandon Blankenagel, Ash Brown, Rebecca Crane, Stephen Frost, Jon Hanson, Ellen Linford, Ben Reese, Loren Ross, and Robert Tuttle assisted with the field testing. Lastly, the author wishes to thank her husband and family, who have been extremely supportive in helping her accomplish this goal.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Chloride penetration into concrete bridge decks is a leading cause of corrosion of reinforcing steel and can lead to rapid deterioration of affected decks (*1, 2, 3, 4, 5*). Chloride ions can initiate corrosion of steel reinforcement at a threshold concentration commonly assumed to be 2.0 lb of chloride per cubic yard of concrete (*6*). Because concrete is relatively weak in tension, the formation of rust, which is approximately 200 percent to 600 percent greater in volume than the parent materials (*7*), leads to cracking and delamination of the concrete deck. The resulting distress in the deck can then reduce the structural integrity and ride quality of the deck, eventually resulting in premature failure of the structure.

This problem is especially paramount in areas where chlorides are prevalent, such as coastal regions that experience salt spray from the ocean 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 (*8*). However, DOTs vary widely in their policies about when surface treatments should be applied and achieve diverse performance results (*9*). 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, concrete cover thickness, and diffusion coefficient of the concrete with which the deck is constructed (*10*). 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, 11, 12, 13*), the literature is generally absent of publications addressing the 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*, *8, 11, 13, 14, 15*) 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 (*7*).

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.

1.2 SCOPE

In cooperation with the Utah Department of Transportation (UDOT), research personnel at Brigham Young University (BYU) performed testing on 12 concrete bridge decks all located within the Interstate 215 (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., 2.5 in., and 3.0 in. The effects of surface treatment placement at times ranging from 1 to 15 years from the date of deck construction were evaluated over a period of 30 years for each combination of parameters.

1.3 OUTLINE OF REPORT

This report contains five chapters. Chapter 1 presents the objectives and scope of the research. In Chapter 2, the results of a literature review addressing diffusion mechanisms, the use of surface treatments in preventive deck maintenance activities, and the effects of SIPMFs on chloride ingress in concrete bridge decks are provided. Descriptions of the experimental plan, field and laboratory testing procedures, and numerical modeling are given in Chapter 3. Test results are explained in Chapter 4 together with a discussion of the research findings. In Chapter 5, summaries of the procedures, research findings, and recommendations are presented.

CHAPTER 2

BACKGROUND

2.1 OVERVIEW

The following sections present the findings of the literature review conducted in this research, including explanations of diffusion mechanisms, the use of surface treatments in preventive deck maintenance activities, and the effects of SIPMFs on chloride ingress in concrete bridge decks.

2.2 DIFFUSION

Diffusion is the movement of ions from areas of higher concentrations to those of lower concentrations (*16*). Ions move in response to spatial differences in entropy between areas having different ion concentrations (*3*). The diffusion of chloride ions begins when salt solutions contact the concrete surface. The ions carried in these solutions diffuse into the concrete matrix and disperse to areas of lower concentration over time (*17*). The rate of diffusion, and therefore the depth of chloride penetration into concrete over a specified time period, is governed by the concentration gradient and a diffusion coefficient (*4*). The greater the diffusion coefficient, the more rapidly chloride ions are able to diffuse through the concrete to the depth of the reinforcing steel.

The presence and continuity of pore water within the concrete matrix directly affect the diffusion coefficient (*1*), where higher degrees of saturation and greater pore water continuity within a concrete structure facilitate more rapid diffusion of chlorides through concrete (*2*). The properties of the concrete pore structure are determined to a large degree by the water-cement 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. Cover thicknesses for concrete bridge decks typically range between 2.0 in. and 3.0 in. (*6*).

2.3 SURFACE TREATMENTS

Adding a surface treatment to the concrete surface is an effective and economical method of disrupting the ingress of chlorides (*8*). Common surface treatment application types for concrete bridge decks include epoxy, epoxy-urethane, methacrylate, and silane (*9*). Although the chemical compositions of these products vary, the products are all promoted for use as barriers against the ingress of both moisture and chlorides. If appropriate materials, deck preparation techniques, and construction methods are utilized, surface treatment applications can prevent the entrance of chlorides into the concrete surface (*14*). Therefore, if placed before chlorides have accumulated in sufficient quantities to cause corrosion of the deck reinforcing steel, surface treatments can prove useful in extending the service life of concrete bridge decks (*1*).

A national questionnaire survey of state DOTs performed in 2004 indicated that 14 of 20 respondents specifically utilize surface treatments for the purpose of acting as a chloride barrier. 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 (*9*). The findings of this survey demonstrate the need for further research on this topic.

2.4 USE OF STAY-IN-PLACE METAL FORMS

The presence of certain construction features, such as SIPMFs, can also affect rates of chloride ingress in concrete bridge decks. Research has shown that decks with SIPMFs are characterized by higher moisture contents; the increase in moisture results from the reduction in exposed deck surface area from which water may evaporate (*5*). Higher moisture, in turn, increases the rate at which chlorides diffuse into the concrete; higher levels of saturation are generally associated with greater continuity within the pore water system, which increases the diffusivity of chloride ions in the concrete matrix (*3, 18*). 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.

2.5 SUMMARY

Chloride diffusion within reinforced concrete bridge decks can be extremely detrimental because chloride ions can lead to the corrosion of reinforcing steel. Adding a surface treatment to the concrete surface is an effective and economical method of disrupting the ingress of chlorides. However, discrepancies about when to apply surface treatments exist among state DOTs. The presence of certain construction features, such as SIPMFs, can also affect rates of chloride ingress in concrete bridge decks. Higher moisture contents, which are typical of decks with SIPMFs, generally correspond to higher diffusion coefficients.

CHAPTER 3
EXPERIMENTAL METHODOLOGY

3.1 OVERVIEW

Field testing, laboratory testing, and numerical modeling were performed to meet the objectives of this research. Chloride concentration data for this research were collected from 12 concrete bridge decks located within the I-215 corridor in Salt Lake City, Utah. UDOT bridge engineers selected six concrete bridge decks with SIPMFs and six without SIPMFs for evaluation. Because of their close geographic proximity and similar highway class, all bridge decks were subject to similar traffic loading, climatic conditions, and maintenance treatments, including the applications of deicing salts during winter months. At the time of testing, the bridges ranged in age from 16 to 21 years. Tables 3.1 and 3.2 provide specific information about decks with SIPMFs and decks without SIPMFs, respectively. A map showing the bridge locations is given in Figure 3.1, in which the black stars represent decks with SIPMFs and the white stars represent decks without SIPMFs.

On each bridge deck, six 6-ft by 6-ft 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 (*19*). Randomizing the test locations within each lane was necessary to ensure that every possible test location had an equal chance of being selected.

TABLE 3.1 Properties of Bridge Decks with SIPMFs

Bridge ID	Year of Deck Construction	Deck Age at Time of Testing (yrs)	Direction of Travel	Actual Direction Tested	Mile Post	Location	Facility	Featured Intersection	Polymer Overlay	Date Testing Performed
C-460	1988	17	NB & SB	NB	21.4	850 S & 2000 W	I-215	Indiana Ave Railroad	No	21-May-05
C-688	1987	18	NB & SB	NB	21.9	500 S & 2000 W	I-215	I-215 & 500 S	No	14-May-05
C-698	1987	18	NB	NB	21.8	500 S & 2000 W	Ramp from I-215 NB to I-80 EB	500 S & Railroad	No	21-May-05
C-699	1987	18	NB	NB	21.8	N of 500 S at 2000 W	Ramp from I-215 NB to I-80	I-215 & Railroad	No	21-May-05
C-759	1989	16	EB & WB	WB	6.5	0.2 mi SW of Knudson Cnr Int	I-215	I-215 & Holladay Blvd	Yes	04-Jun-05
C-760	1989	16	WB	WB	6.5	0.2 mi SW of Knudson Cnr Int	On-ramp to I-215 WB	I-215 & Holladay Blvd	No	04-Jun-05

TABLE 3.2 Properties of Bridge Decks without SIPMFs

Bridge ID	Year of Deck Construction	Deck Age at Time of Testing (yrs)	Direction of Travel	Actual Direction Tested	Mile Post	Location	Facility	Featured Intersection	Polymer Overlay	Date Testing Performed
C-726	1984	21	NB & SB	NB	9.5	6550 S & 900 E	SR-71 (900 E)	I-215 & 900 E	No	16-Jul-05
C-736	1987	18	WB	WB	7.7	6600 S & 2000 E	On-ramp to I-215 WB	I-215 & SR-152	Yes	30-Jul-05
C-752	1988	17	NB & SB	NB	20.6	W Redwood Rd at California Ave	I-215	I-215 & California Ave	Yes	14-May-05
F-500	1984	21	NB & SB	NB	23.3	700 N & 2000 W	I-215	I-215 & 700 N	No	16-Jul-05
F-504	1984	21	NB & SB	SB	8.0	6650 S & 1300 E	1300 East	I-215 & 1300 E	No	04-Jun-05
F-506	1985	20	NB & SB	NB	8.1	2300 E & 6450 S	2300 South	I-215 & 2300 S	No	16-Jul-05

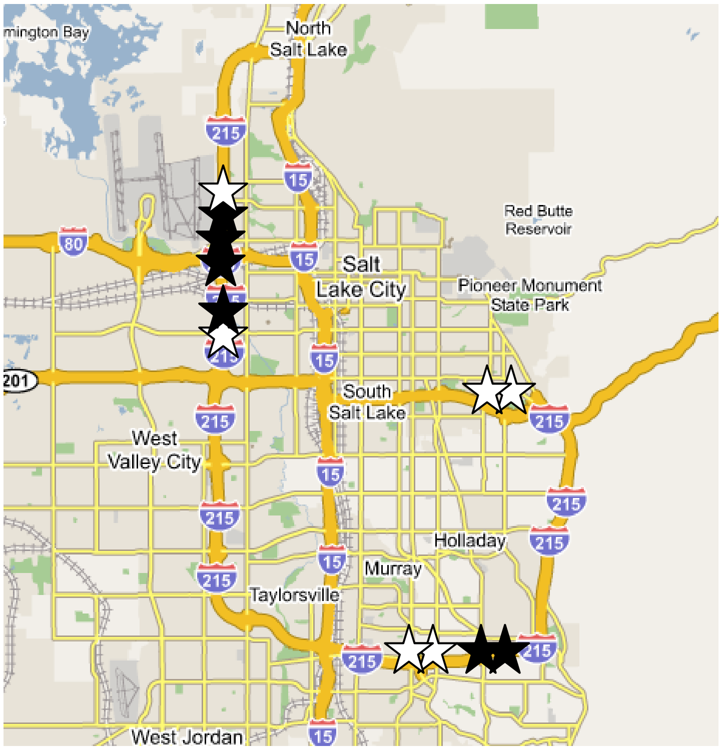
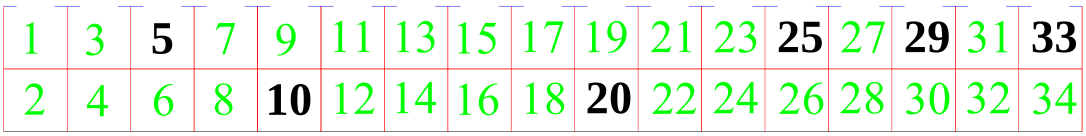


FIGURE 3.1 Bridge deck locations.

In randomizing the test locations on each bridge deck, the researchers first measured the length of each deck in units of feet and then multiplied that value by two and divided it by six to compute the number of available test areas on the deck. Finally, the total number of available test areas was multiplied by six random numbers between zero and one. The same random numbers, which are shown in Table 3.3, were used for all 12 bridge decks. Figure 3.2 displays the relative locations of the randomly selected test areas on a hypothetical deck 100 ft in length; the test areas are marked using bold-faced numbering.

TABLE 3.3 List of Random Numbers

Random Numbers
0.1493
0.2956
0.5765
0.7241
0.8450
0.9573



1	3	**5**	7	9	11	13	15	17	19	21	23	**25**	27	**29**	31	**33**
2	4	6	8	**10**	12	14	16	18	**20**	22	24	26	28	30	32	34

FIGURE 3.2 Example selection of test areas for 100-ft deck.

3.2 FIELD TESTING

Chloride extractions were performed in one location within each test area. A cover meter was used, as shown in Figure 3.3, to establish the location of rebar within each test area. Locating the rebar was necessary so that, during sample extraction, the hammer drill operator could avoid drilling into reinforcing steel. Each extraction was accomplished in approximately 1-in. lifts using four different hammer drill bits, which ranged in size from 0.75 in. to 1.5 in. in diameter. On bridge decks with SIPMFs, seven or eight lifts were removed, 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 by 0.25 in. after every two lifts to minimize contamination of deeper samples that may have otherwise occurred by inadvertently scraping the sides of previous lifts during the drilling process. A schematic showing the reductions in bit diameter with increasing depth is shown in Figure 3.4, and a picture of a typical hole resulting from this practice is shown in Figure 3.5.

After each lift was pulverized, the concrete sample was manually removed from the hole and placed into a plastic bag, as illustrated in Figure 3.6. 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 calculation of chloride concentration profiles. The drilling process was then repeated until the seven or eight lifts were completed.

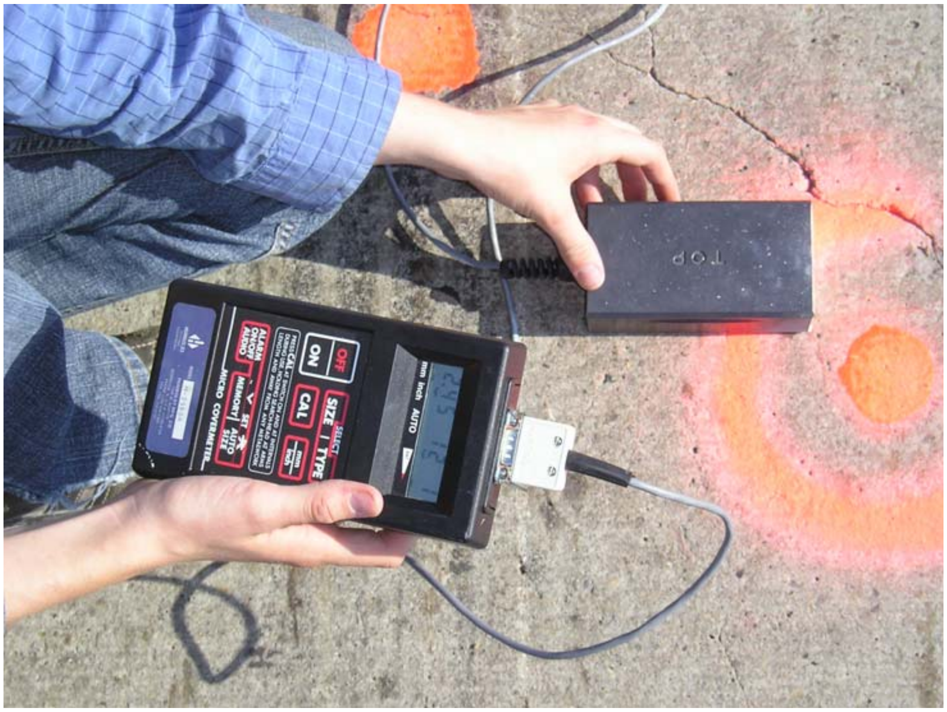


FIGURE 3.3 Cover meter used to locate rebar.

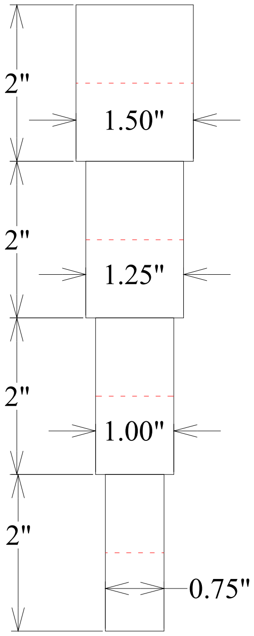


FIGURE 3.4 Hole dimensions for chloride concentration sampling.

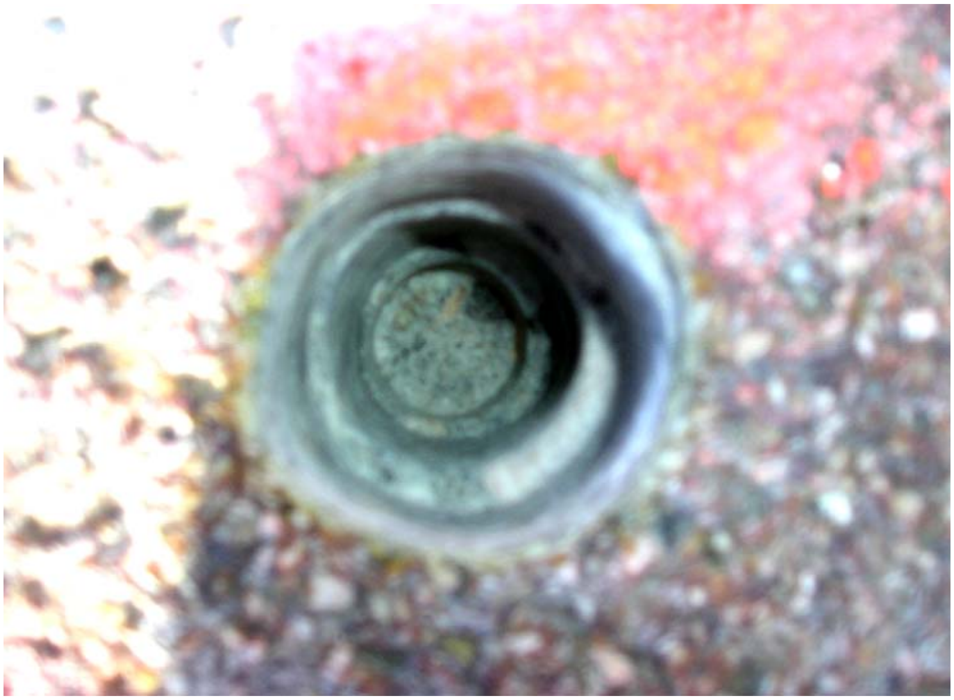


FIGURE 3.5 Example of a typical hole after drilling.

FIGURE 3.6 Removal of pulverized concrete from drilled hole.

3.3 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. The requirement in this standard for the sample to pass through a No. 50 (0.0018-in.) sieve was satisfied by using a hammer drill for sample extraction, which facilitated adequate pulverization of the concrete in the field. This test protocol required boiling of 0.35-oz. samples in water for 5 minutes and a subsequent 24-hour cooling period. After cooling, the solution was filtered, as illustrated in Figure 3.7, and treated with equal amounts of nitric acid and hydrogen peroxide. As demonstrated in Figure 3.8, the chloride concentration of the solution was then measured using a laboratory chloride-ion-selective probe. When required, units of moles per liter, or molarity, were converted to pounds of chloride per cubic yard of concrete based on the initial weight of each sample and an assumed concrete density of 145 lb/ft^3.

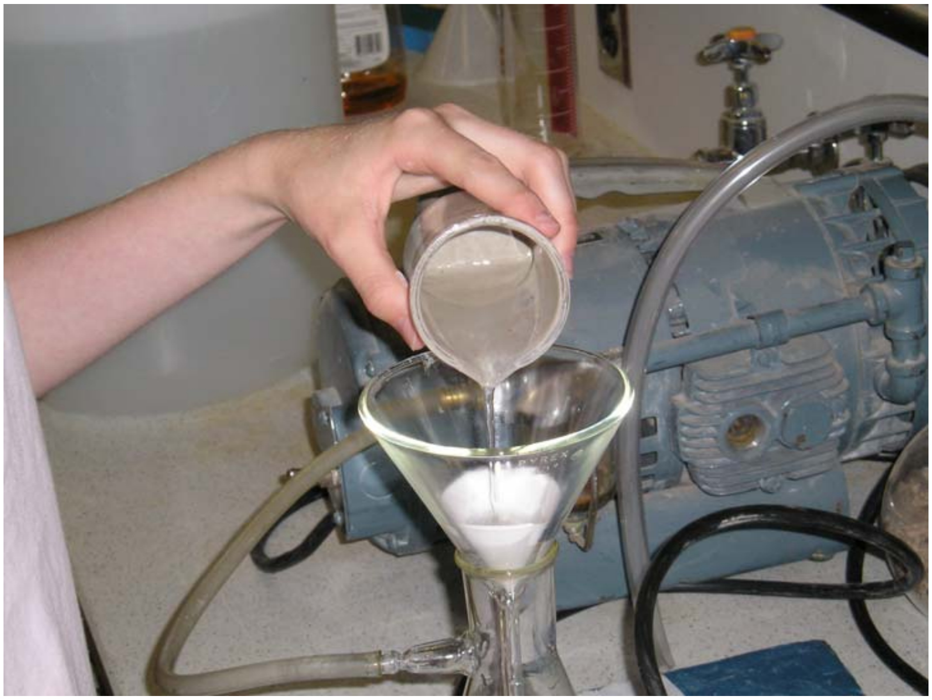


FIGURE 3.7 Filtering a chloride concentration sample.

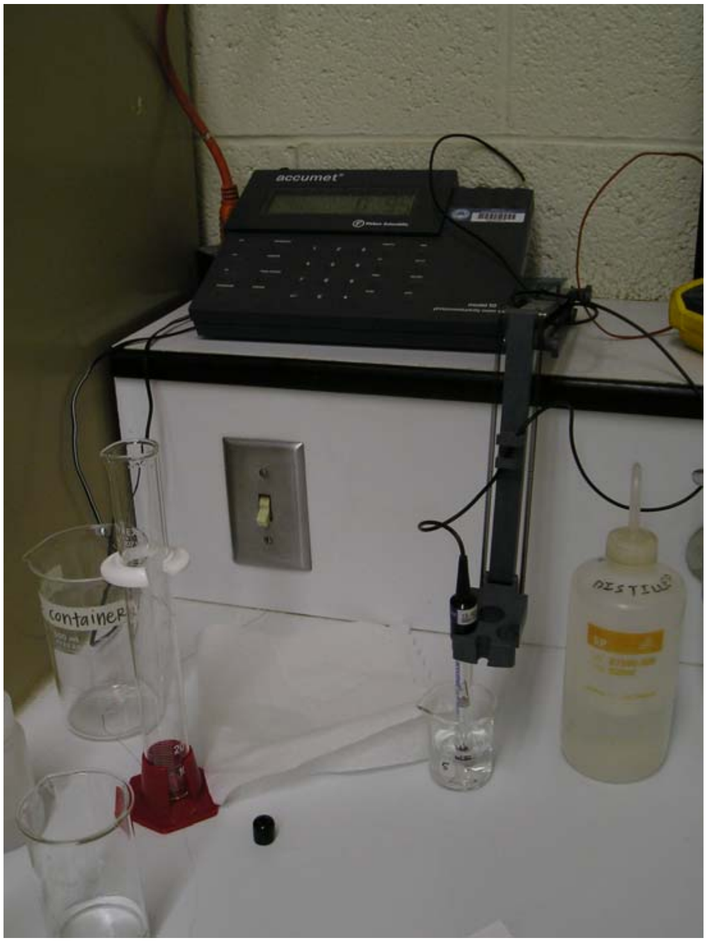


FIGURE 3.8 Measuring the chloride concentration.

3.4 NUMERICAL MODELING

To facilitate analysis of chloride concentration profiles, the midpoint of each depth interval was computed, and chloride concentrations at 1-in. depth intervals were then determined for each test location by linear interpolation. For use in determining diffusion coefficients, the average chloride concentration associated with each depth interval was also computed for each deck from the six chloride profiles prepared from the six test locations.

Numerical modeling was performed using measured chloride profiles and a computer program developed at the National Institute of Standards and Technology (NIST) (*10*). 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 typically specified by UDOT for construction of bridge decks, which is presented in Table 3.4; and information published in the literature (*20, 21*). 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. Input variables held constant for each bridge deck are presented in Table 3.5. (Because the program utilizes metric units, data associated with the program operation are also presented in metric units.)

The total duration of exposure to chlorides was specified separately for each individual deck based on its age. 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.

TABLE 3.4 Concrete Mixture Design

Ingredient	Weight (lb)	Specific Gravity	Volume (yd^3)
Coarse Aggregate (SSD)	1714	2.55	0.399
Fine Aggregate (SSD)	1071	2.60	0.244
Cement	519	3.15	0.098
Fly Ash	115	2.30	0.030
Free Water	280	1.00	0.166
Water Reducer	1.19	1.00	0.001
Air	-	-	0.063

TABLE 3.5 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/mole)	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

The first step in the numerical modeling process was to determine the surface chloride concentrations as they varied with time during a typical year. These values were determined on a monthly basis and assumed to remain constant from year to year. In order to calculate these values, a function was derived based on previous research (*22*), and parameters in the equation were selected using an optimization process that provided the best matches overall between measured and simulated chloride concentration profiles for decks with and without SIPMFs. Due to deicing salt application during winter months, the resulting equation representing the monthly chloride concentrations was a sinusoidal function.

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. depth intervals. 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 was 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. 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. Bridge decks were assumed to be protected from chloride ingress from the time the first treatment is applied through the end of the simulation at a deck age of 30 years. The effects of surface treatment placement at 1 to 15 years after deck construction were investigated in this manner for three different cover thicknesses. Cover thicknesses of 2.0 in., 2.5 in., and 3.0 in. were chosen based on national averages given by DOTs in a survey concerning bridge decks (*6*). 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 top mat of deck reinforcement during the 30-year period. The values were compared to the threshold value of 2.0 lb of chloride per cubic yard of concrete to identify the recommended timing of initial surface treatment application in each case.

3.5 SUMMARY

In order to assess possible differences in chloride diffusion coefficients between decks with SIPMFs and those without SIPMFs, BYU research personnel evaluated six bridge decks of each deck type. Because all 12 decks were located within the I-215 corridor in the vicinity of Salt Lake City, Utah, and were of similar highway class, they were subject to similar traffic loading, climatic conditions, and maintenance treatments, including applications of deicing salts during winter months. Chloride concentration testing was performed within each of the six randomly selected test areas on each deck. The collected samples were then returned to BYU for evaluation of the chloride concentration. The measured chloride concentrations were then used in numerical modeling to determine the average diffusion coefficient and recommended timing of surface treatment applications for bridge decks with and without SIPMFs.

CHAPTER 4

RESULTS

4.1 OVERVIEW

The results of field and laboratory testing and numerical modeling are presented in the following sections.

4.2 FIELD AND LABORATORY TESTING

The results of this research include both measured and simulated chloride concentrations. Measured data are given in Table 4.1, which displays the average chloride concentrations computed at 1-in. depth intervals for each deck. A hyphen in the table indicates that no sample was taken at that depth, usually because the thickness of the deck was less than 8 in. or because the depth of the drilling was limited to less than 8 in. to facilitate patching of the test holes.

TABLE 4.1 Measured Chloride Concentrations

(a) Decks with SIPMFs

Depth (in.)	Average Chloride Concentration (M)					
	Deck ID					
	C-688	C-698	C-699	C-460	C-759	C-760
1	1.856	2.666	2.309	2.234	1.536	2.697
2	1.033	1.560	1.521	1.000	1.042	1.577
3	0.497	0.771	0.908	0.435	0.610	0.839
4	0.160	0.336	0.449	0.190	0.317	0.385
5	0.078	0.106	0.166	0.087	0.115	0.135
6	0.031	0.029	0.059	0.048	0.037	0.044
7	0.015	0.008	0.035	0.030	0.019	0.018
8	-	0.001	-	-	0.009	-

TABLE 4.1 Measured Chloride Concentrations, Continued

(b) Decks without SIPMFs

Depth (in.)	Average Chloride Concentration (M)					
	Deck ID					
	C-726	C-736	C-752	F-500	F-504	F-506
1	2.254	1.755	1.749	1.085	2.085	1.951
2	1.595	0.545	0.355	0.102	1.084	0.935
3	0.774	0.045	0.083	0.016	0.415	0.159
4	0.238	0.017	0.041	0.007	0.124	0.052
5	0.044	0.007	0.031	0.006	0.020	0.007
6	0.006	0.011	0.030	0.005	0.005	0.005
7	0.004	0.015	0.026	0.006	0.005	0.005
8	-	-	-	-	-	-

4.3 NUMERICAL MODELING

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

$$C = 3.3 + 1.1 \cdot \cos\left(\frac{\pi \cdot t}{6} - 1\right) \qquad (1)$$

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

A plot of Equation 1 is shown in Figure 4.1. The surface chloride concentration produced by the function ranges from 2.6 mol/L to 5.0 mol/L.

The calculated diffusion coefficients for each deck are shown in Table 4.2. 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 (*2*).

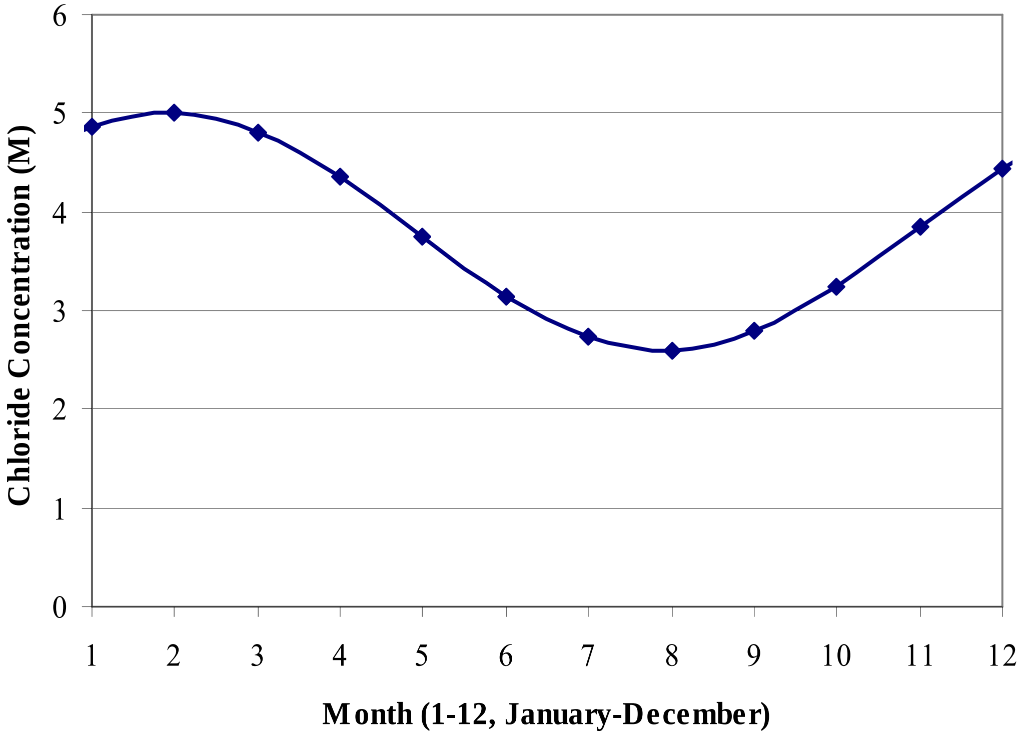


FIGURE 4.1 Surface chloride concentrations by month.

As reported in Tables 3.1 and 3.2, bridge decks C-759, C-736, and C-752 had surface treatments in place at the time of field testing, but they were modeled in the NIST computer program as if they had bare, concrete surfaces; unfortunately, because UDOT does not record the dates on which surface treatments are applied to bridge decks within the state, the exact effects of the surface treatments on the chloride profiles of the affected decks could not be investigated in this study. However, given that the surface treatments were likely applied between one and three years prior to the field testing, the decks were of sufficient age that the chloride profiles were probably not significantly affected by the applications. As displayed in Table 4.2, the effect of an existing surface treatment is not evident in the diffusion coefficient results. That is, the diffusion coefficients computed for the three decks with surface treatments are not remarkably different from the diffusion coefficients calculated for the other decks in the same categories.

TABLE 4.2 Calculated Diffusion Coefficients

(a) Decks with SIPMFs

Deck ID	Diffusion Coefficient (m^2/s)
C-688	2.05E-11
C-698	3.20E-11
C-699	3.35E-11
C-460	1.90E-11
C-759	2.05E-11
C-760	3.75E-11
Average	2.72E-11

(b) Decks without SIPMFs

Deck ID	Diffusion Coefficient (m^2/s)
C-726	2.55E-11
C-736	1.00E-11
C-752	0.91E-11
F-500	0.37E-11
F-504	1.65E-11
F-506	1.30E-11
Average	1.30E-11

Following diffusion coefficient computations, the effects of initial surface treatment application at varying deck ages were simulated using the NIST computer program. The program simulated the ingress of chlorides from the date of deck construction until placement of the surface treatment and the redistribution of existing chlorides in the deck after placement of the surface treatment through the remainder of the 30-year analysis period utilized in this research. The results of surface treatment placement on bridge decks with SIPMFs from 1 to 15 years after deck construction are shown in Appendix A in Figures A.1 to A.16. The results of surface treatment placement on bridge decks without SIPMFs from 1 to 15 years after deck construction are presented in Appendix B in Figures B.1 to B.16.

Chloride concentrations at cover thicknesses of 2.0 in., 2.5 in., and 3.0 in. were determined from each of these graphs and compiled to form graphs demonstrating the effect of surface treatment placement on chloride concentrations at the depth of the deck reinforcement. These resulting graphs are shown in Figures 4.1 to 4.6 for a 30-year period of deck life, where Figures 4.1 to 4.3 represent decks with SIPMFs and Figures 4.4 to 4.6 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 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 downwards into the deck toward a condition of equilibrium. In Figure 4.2, a surface treatment applied at 2 years demonstrates this trend. When the surface treatment is applied, the chloride concentration at the level of the reinforcement is below the threshold concentration of 2 lb of chloride per cubic yard of concrete, but at approximately 3 years the chloride concentration exceeds the threshold value at that depth. Over time, the chlorides diffuse downward, reducing the concentration of chlorides in the vicinity of the steel to about 0.4 lb of chloride per cubic yard of concrete, which is below the threshold value, after 30 years. 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 recommended 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. 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. For decks with SIPMFs and a 3-in. cover, additional modeling was performed to ensure that 15 years is the recommended timing for placement of the surface treatment; modeling a surface treatment applied at 16 years from the date of deck construction yielded chloride concentrations greater than the threshold value.

Table 4.3 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. of cover beyond 2.0 in. 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.

The individual surface treatment applications proposed in this research are suggestions for the initial application only. Surface treatments may only last for a certain number of years, so repeated applications may be necessary to ensure that chlorides do not eventually enter the concrete deck.

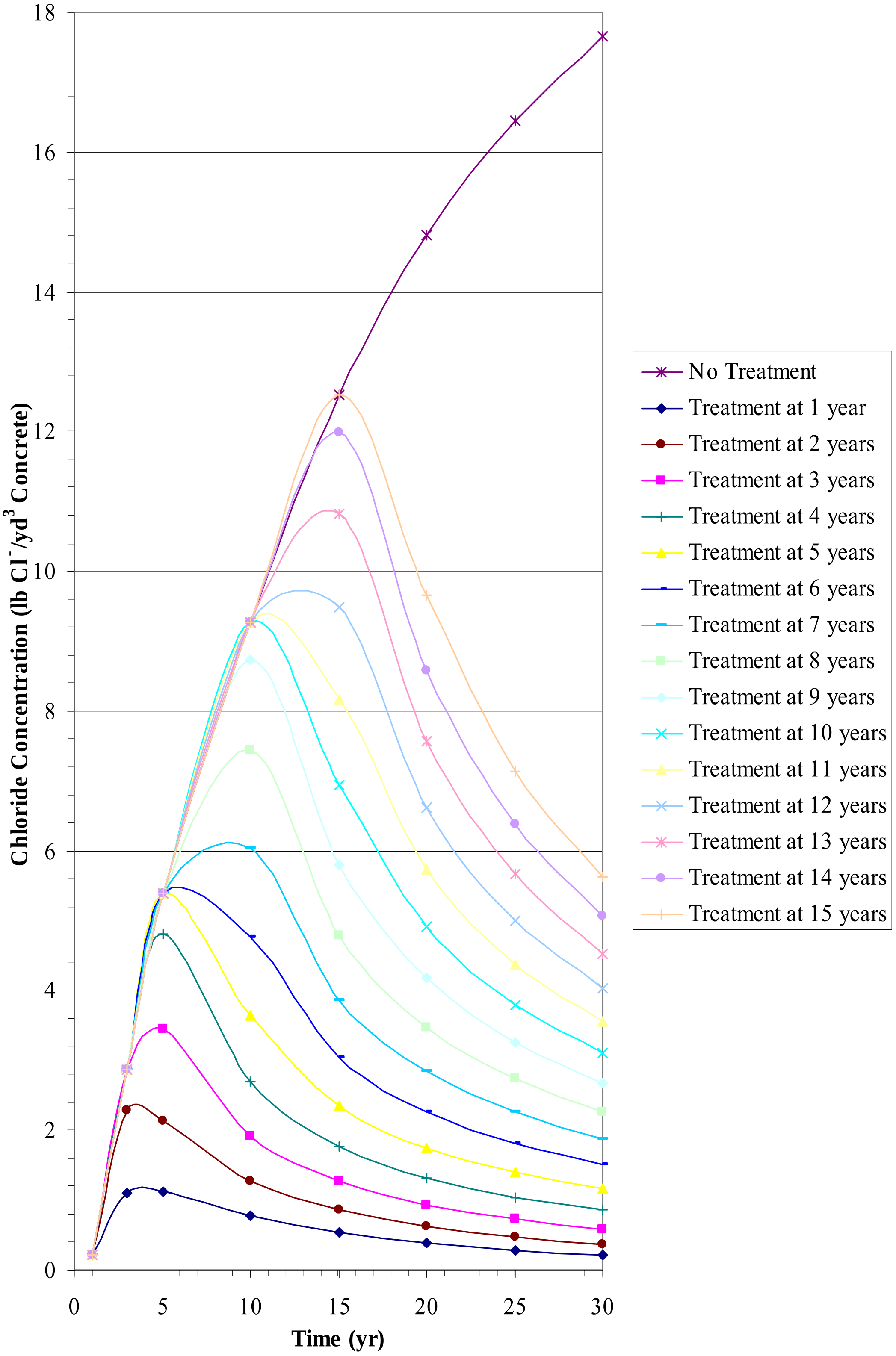


FIGURE 4.2 Chloride concentrations of decks with SIPMFs at a 2.0-in. cover depth.

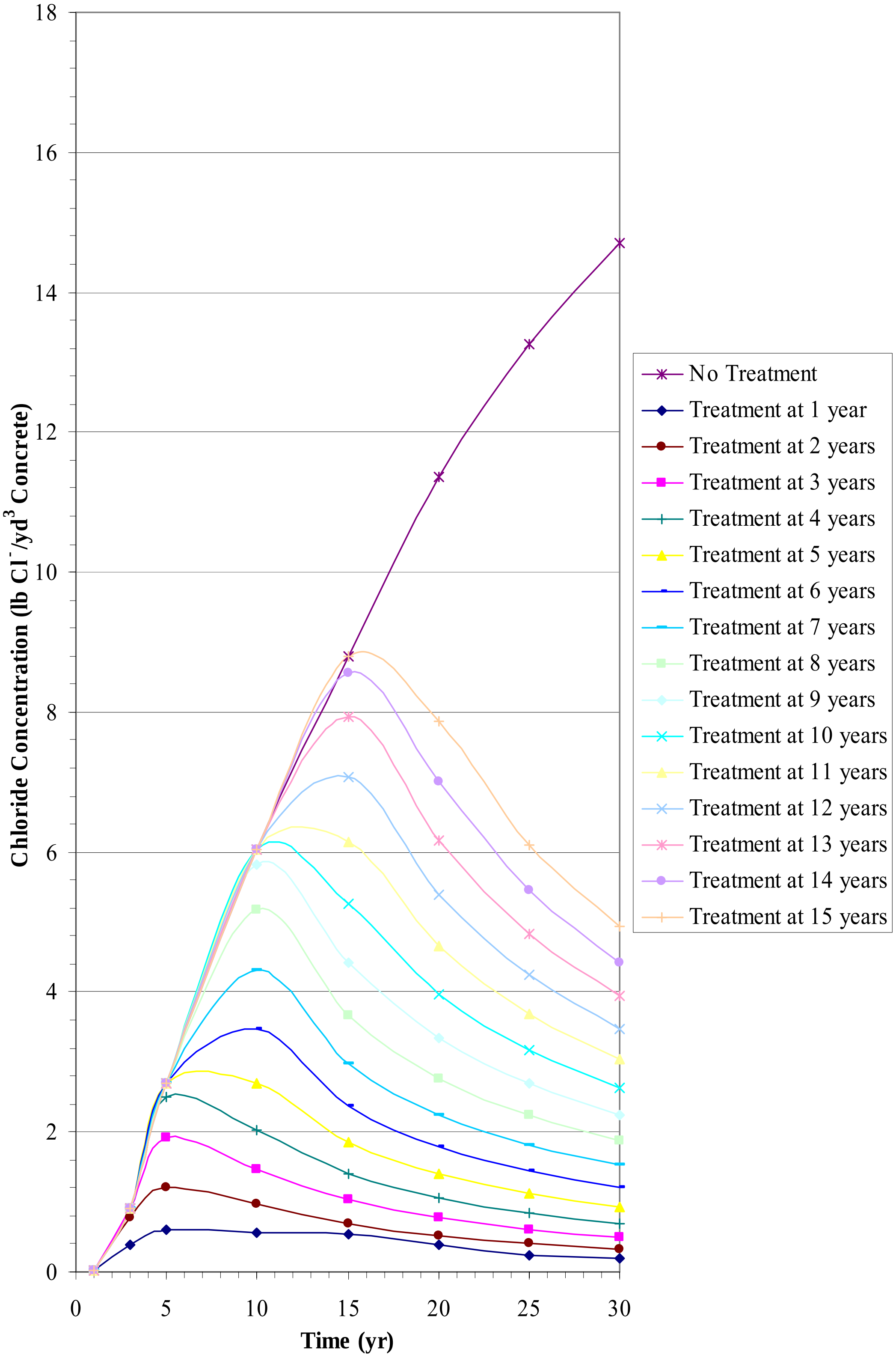


FIGURE 4.3 Chloride concentrations of decks with SIPMFs at a 2.5-in. cover depth.

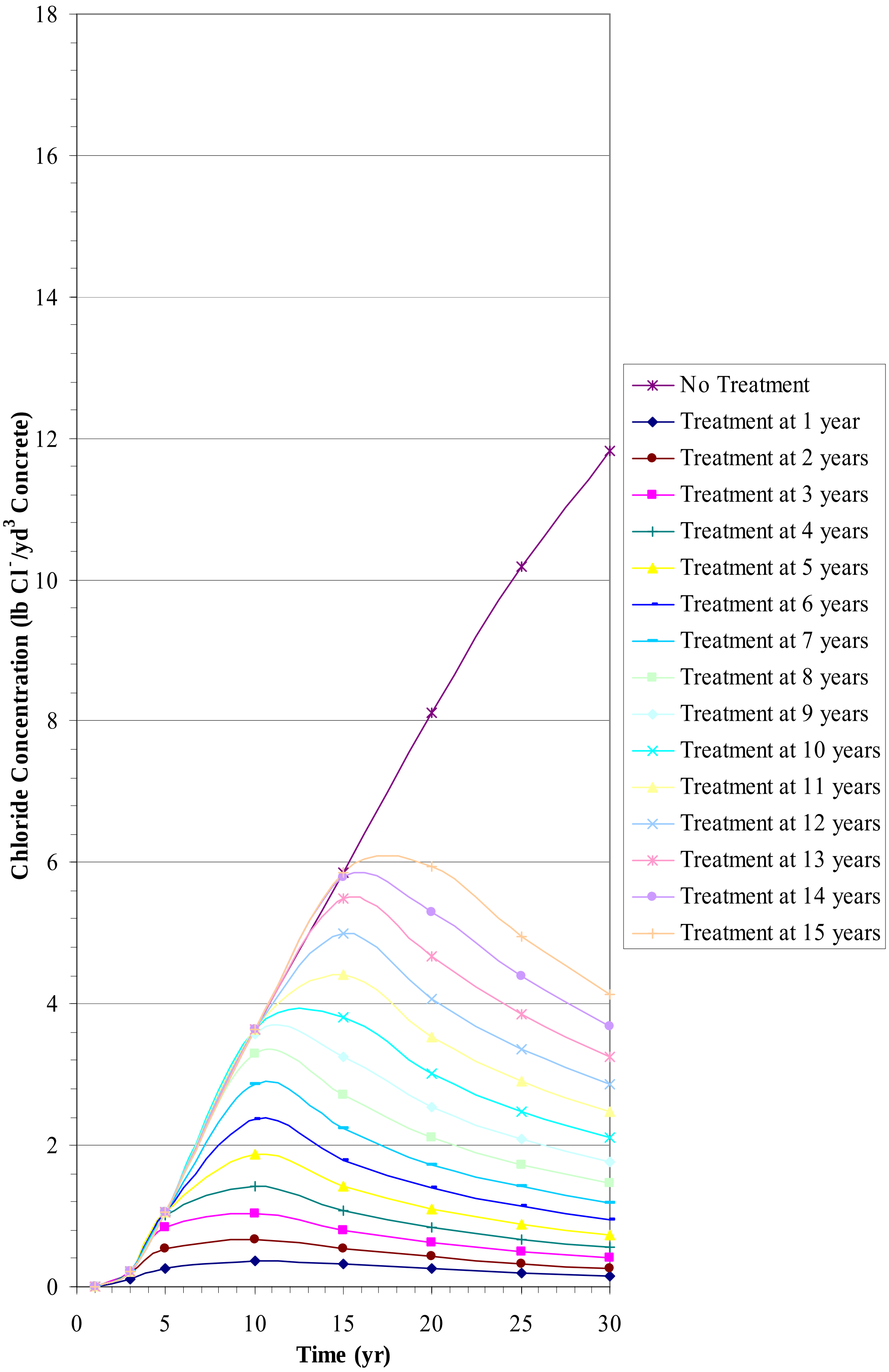


FIGURE 4.4 Chloride concentrations of decks with SIPMFs at a 3.0-in. cover depth.

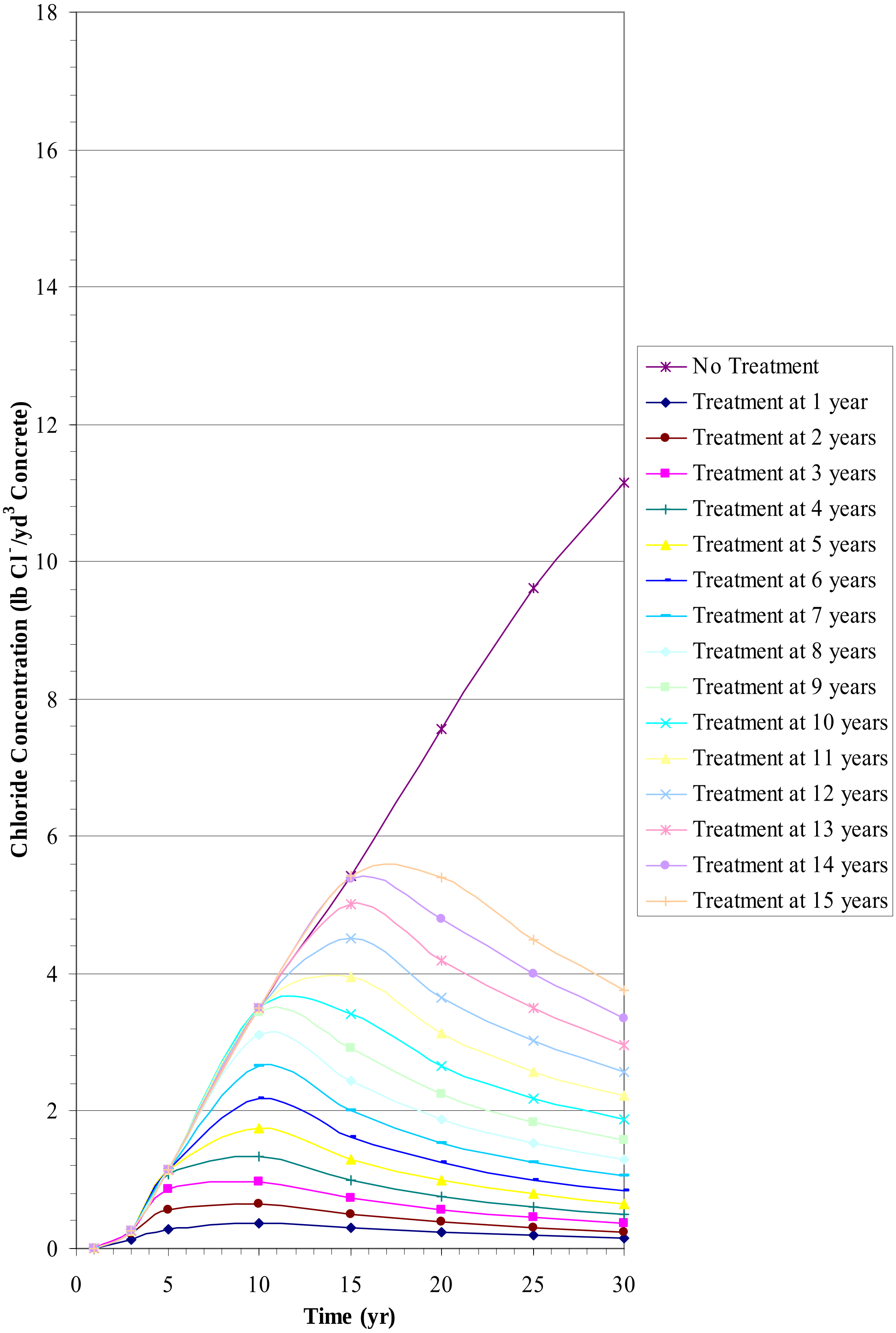


FIGURE 4.5 Chloride concentrations of decks without SIPMFs at a 2.0-in. cover depth.

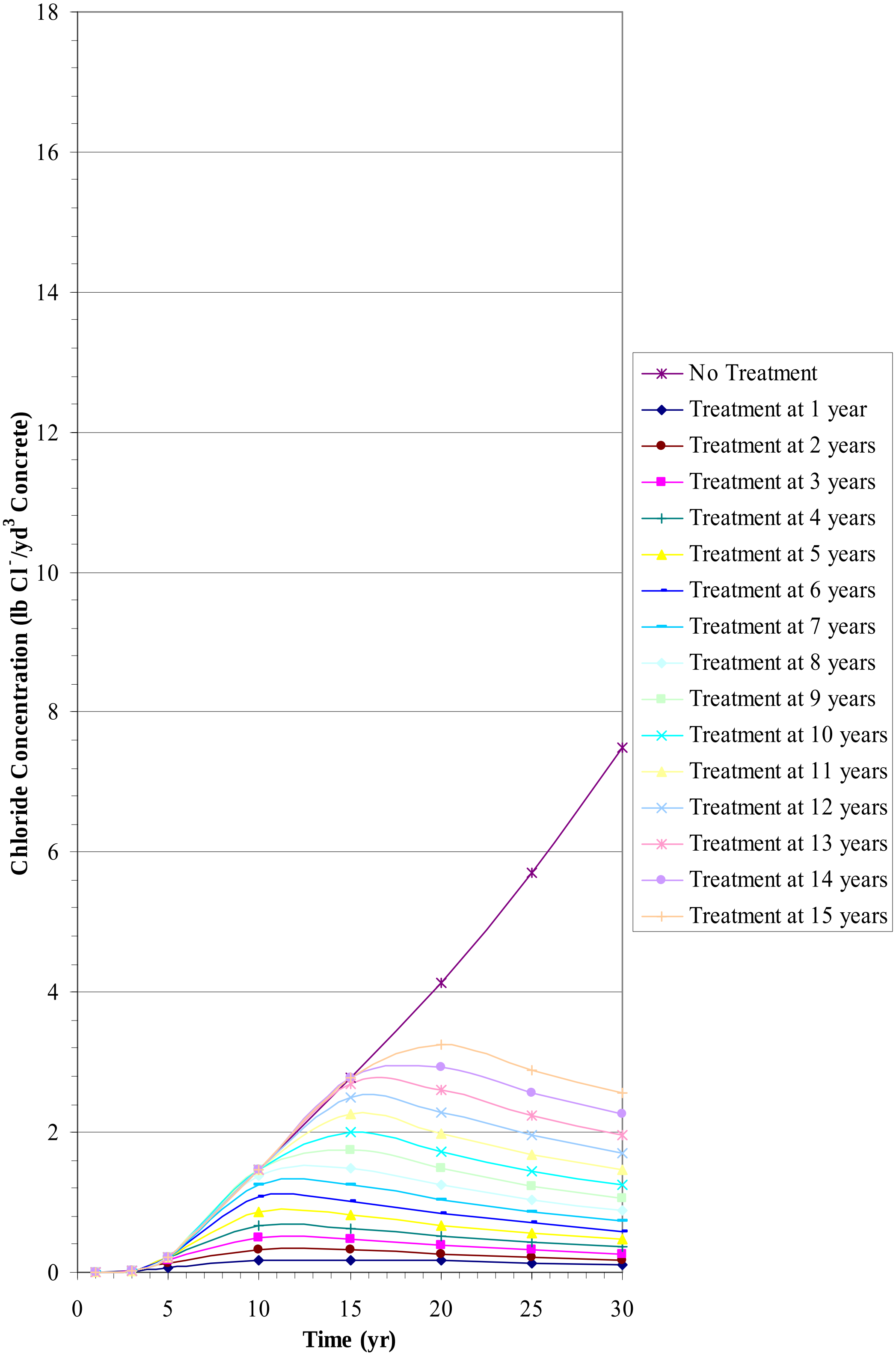


FIGURE 4.6 Chloride concentrations of decks without SIPMFs at a 2.5-in. cover depth.

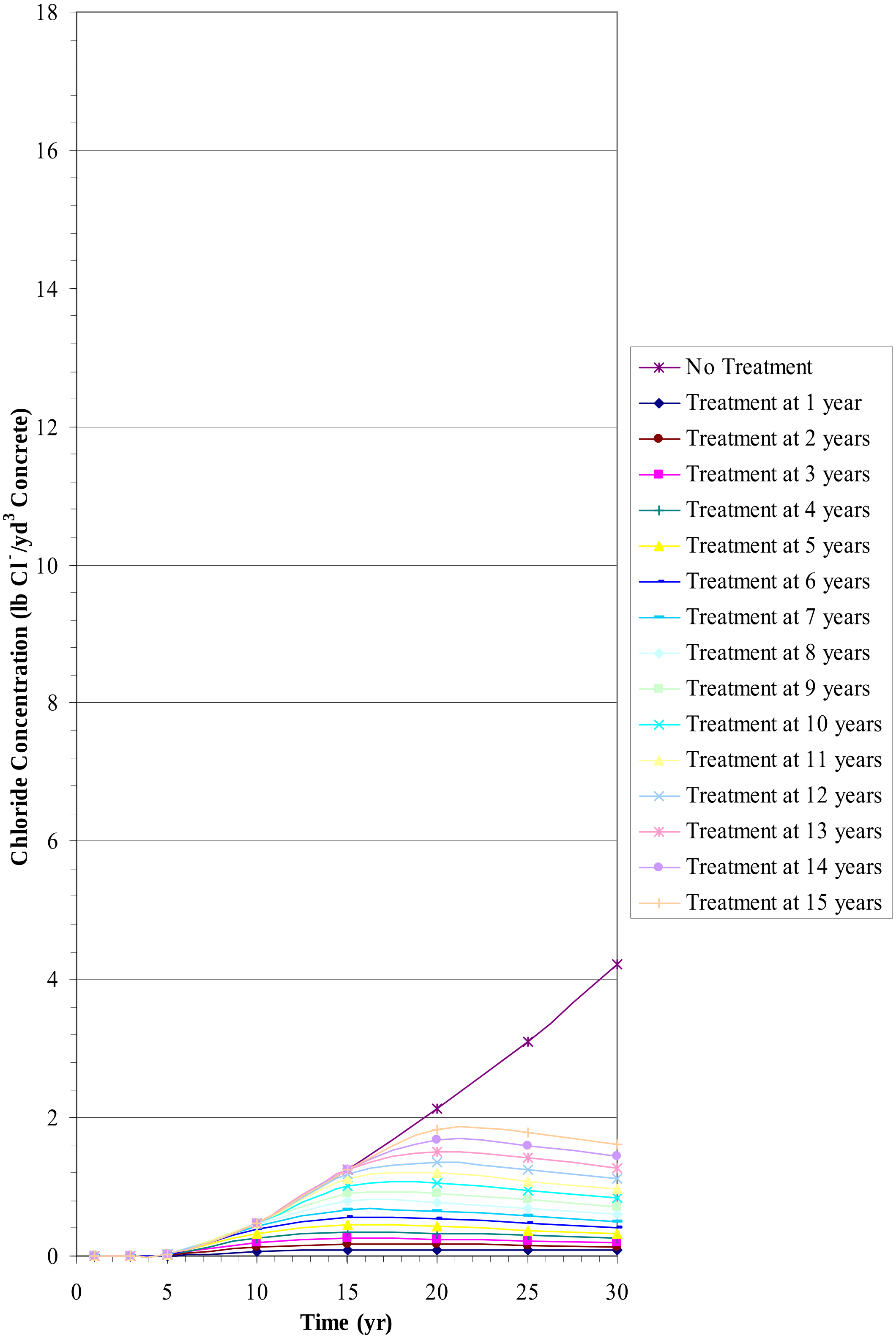


FIGURE 4.7 Chloride concentrations of decks without SIPMFs at a 3.0-in. cover depth.

TABLE 4.3 Recommended Initial Timing of Surface Treatment Applications

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

4.4 SUMMARY

The results of this research include both measured and simulated chloride concentrations. The average diffusion coefficient for bridge decks with SIPMFs is approximately twice that of decks without SIPMFs, as explained by the fact that the presence of SIPMFs leads to more rapid diffusion of chlorides into the concrete. Following diffusion coefficient computations, the effects of surface treatment application at varying deck ages was simulated using the NIST computer program. Chloride concentrations at cover thicknesses of 2.0 in., 2.5 in., and 3.0 in. were determined from each of the resulting graphs and compiled to form additional graphs demonstrating the effect of surface treatment placement on chloride concentrations at the depth of the top mat of deck reinforcement. Based on the figures, the recommended timing of 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. Greater cover depths allow longer delays in surface treatment placements following deck construction; on average, each additional 0.5 in. of cover beyond 2.0 in. 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.

CHAPTER 5

CONCLUSION

5.1 SUMMARY

Recognizing the need to minimize the corrosion of reinforcing steel in concrete bridge decks, 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 on concrete bridge decks subjected to external chloride loading 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. On each bridge deck, six randomly distributed 6-ft by 6-ft test locations were evaluated within the single lane closed for testing. After field and laboratory testing, 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., 2.5 in., and 3.0 in.

5.2 FINDINGS

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. of cover beyond 2.0 in. allows an extra 2 years for decks with SIPMFs and 5 years for decks without SIPMFs before the initial 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. 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.

5.3 RECOMMENDATIONS

Given these research findings, engineers should carefully determine the appropriate timing for initial applications of surface treatments to concrete bridge decks in consideration of cover depth and the presence of SIPMFs. For maintenance of concrete bridge decks with properties similar to those tested in this study, engineers should follow the guidelines developed in this research to minimize the ingress of chlorides into the concrete over time and therefore retard the onset of reinforcement corrosion; altogether separate guidelines may be needed for decks having substantially different properties. Surface treatments should be replaced as needed to ensure continuing protection of the concrete bridge deck against chloride ingress.

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APPENDIX A:

CHLORIDE CONCENTRATIONS OF DECKS WITH SIPMFS

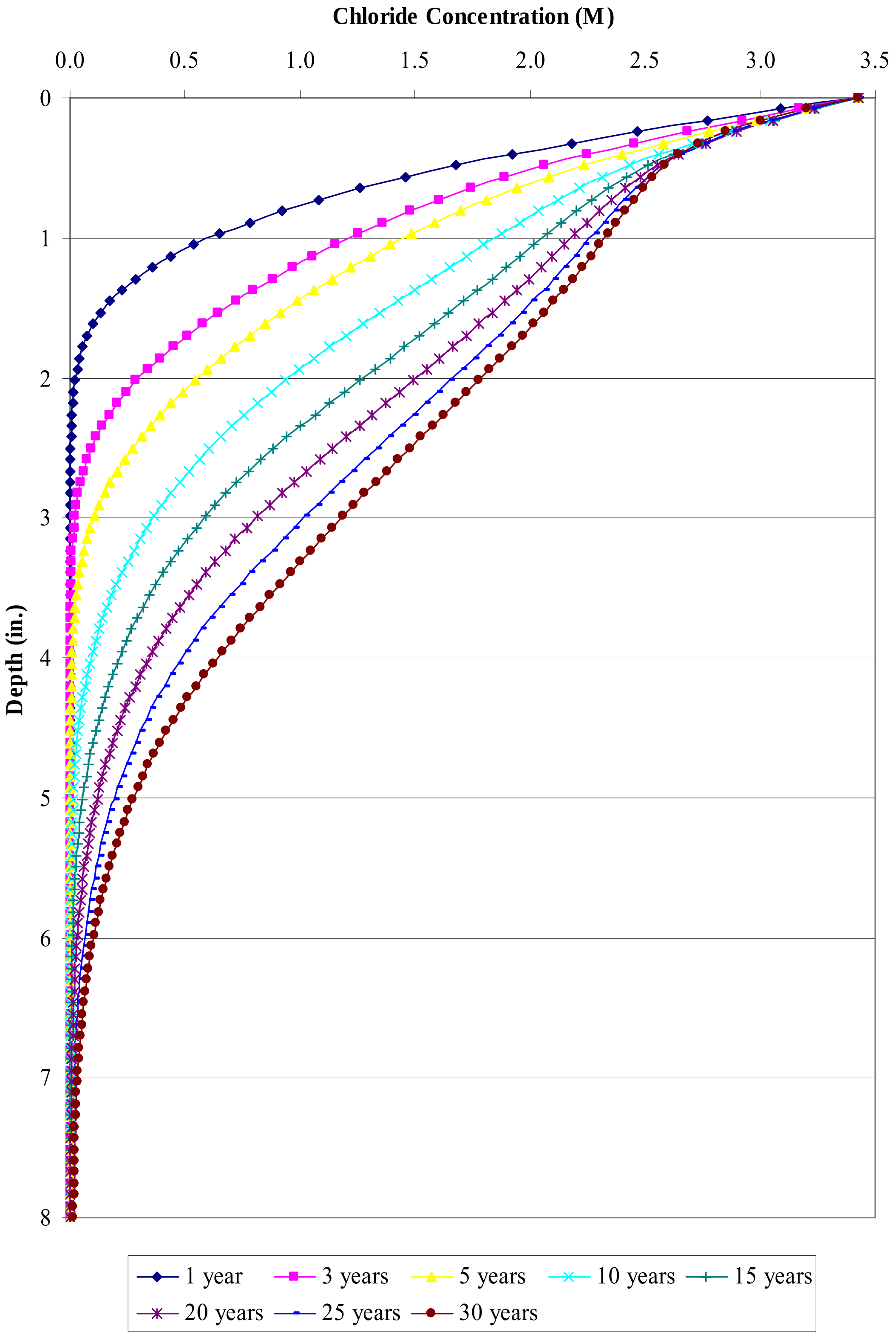

FIGURE A.1 Chloride concentrations of decks with SIPMFs with no surface treatment applied.

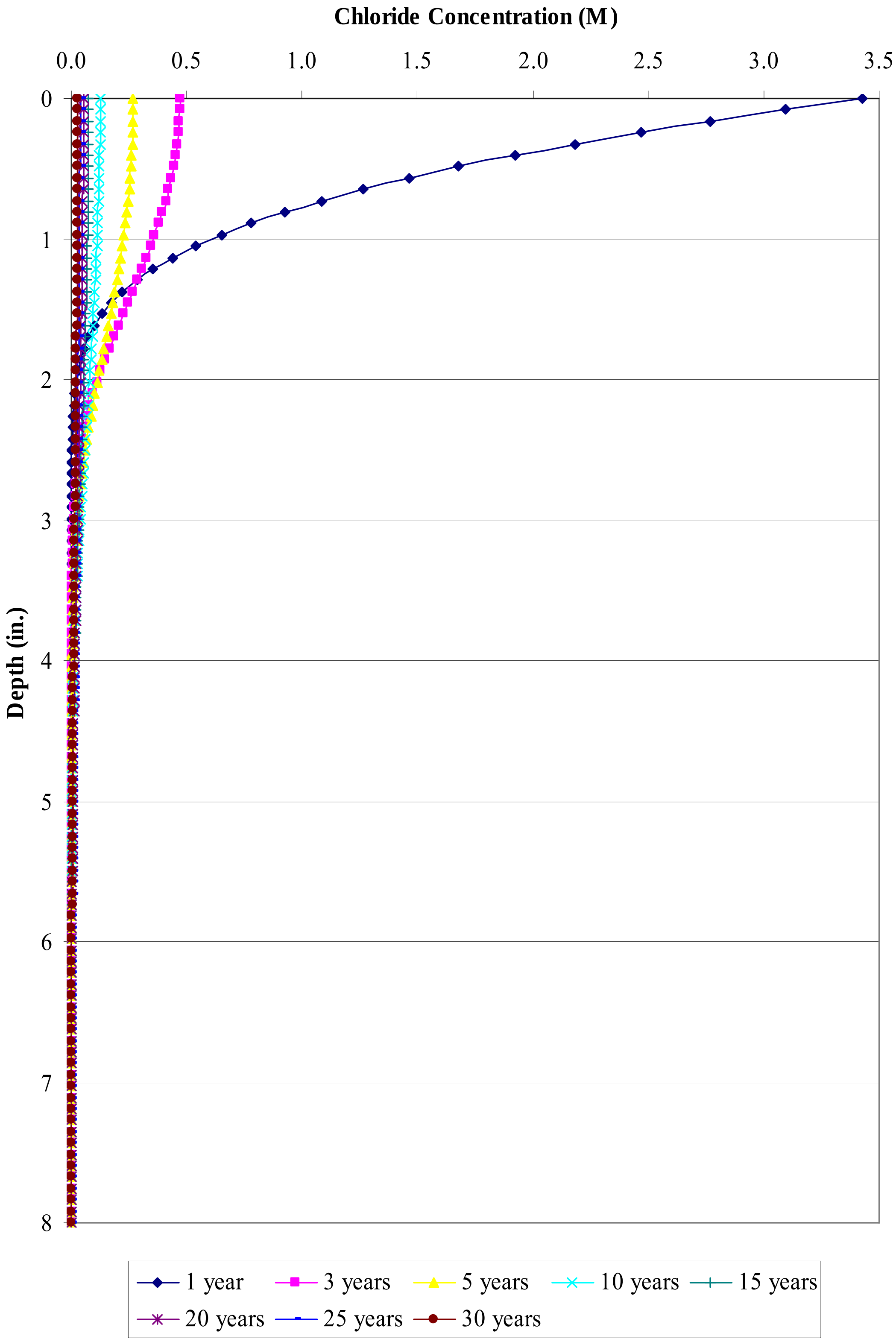

FIGURE A.2 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 1 year.

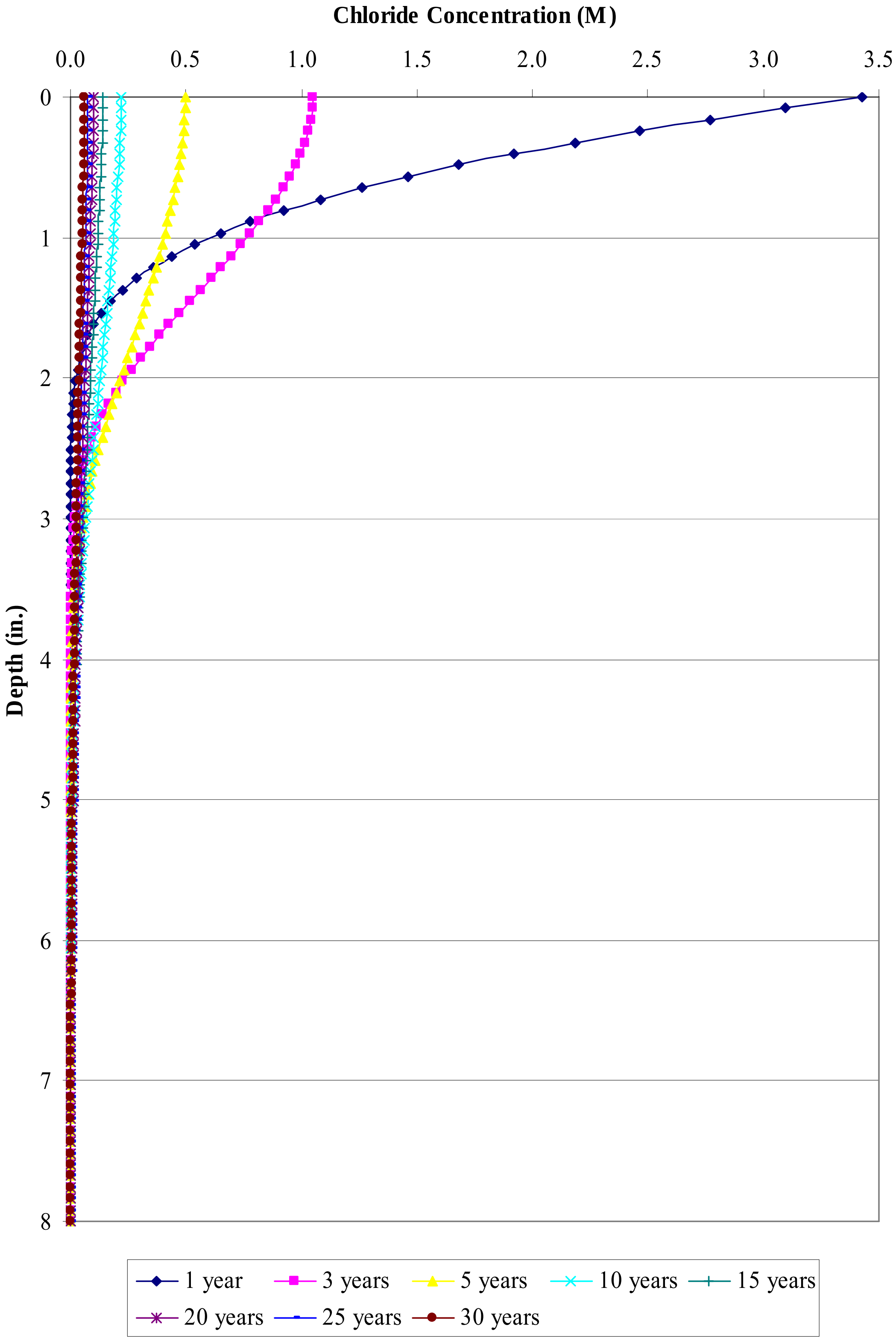

FIGURE A.3 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 2 years.

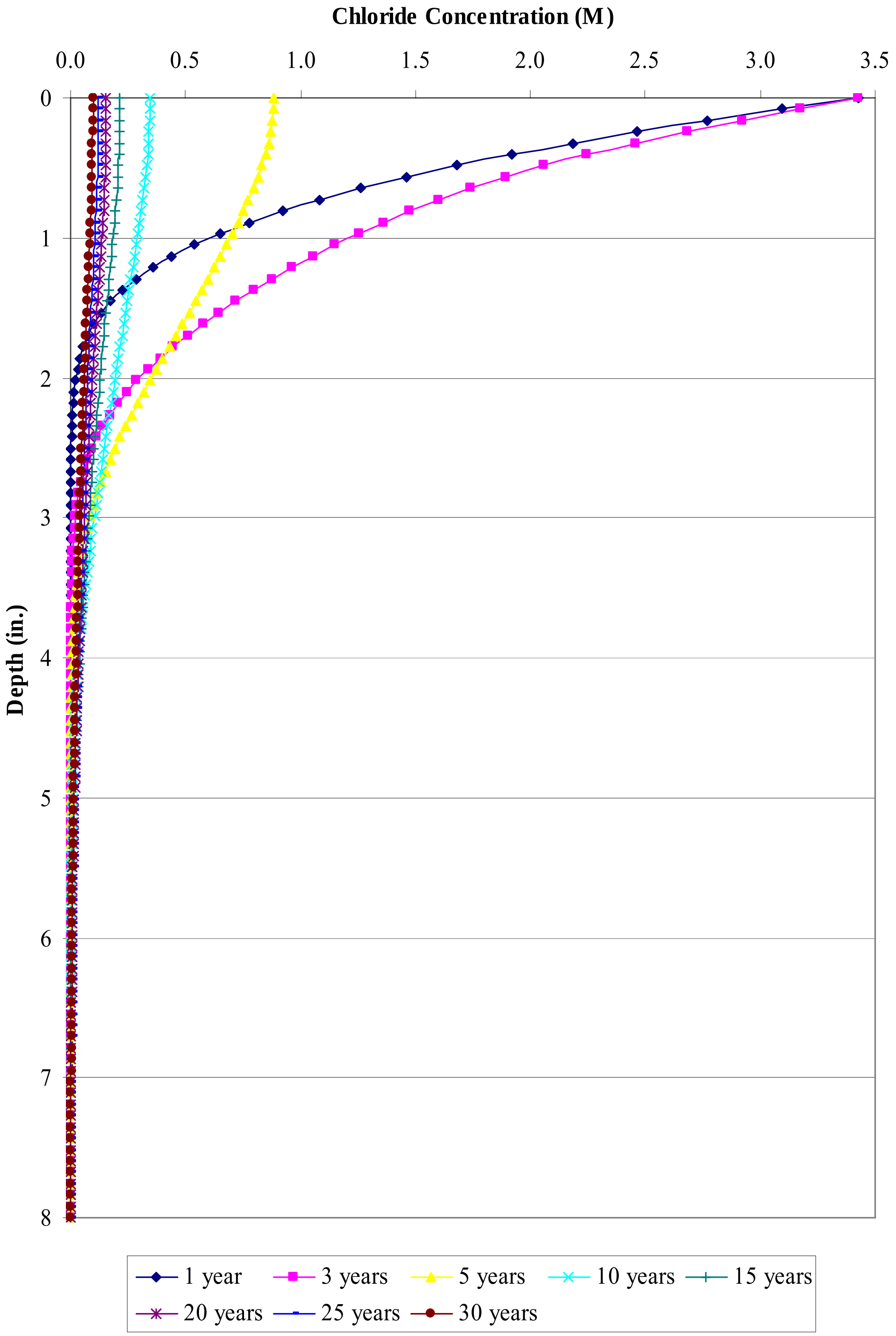

FIGURE A.4 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 3 years.

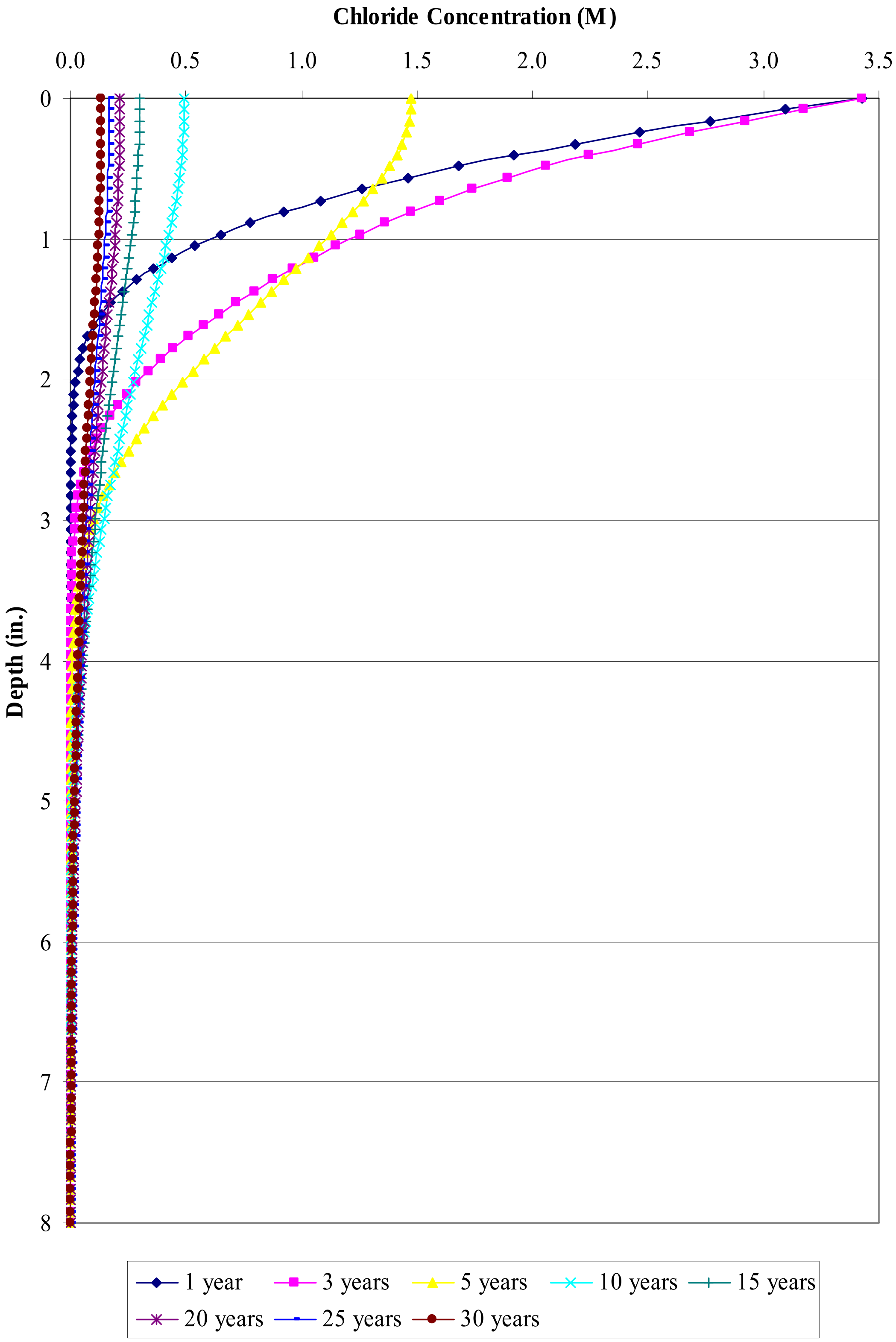

FIGURE A.5 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 4 years.

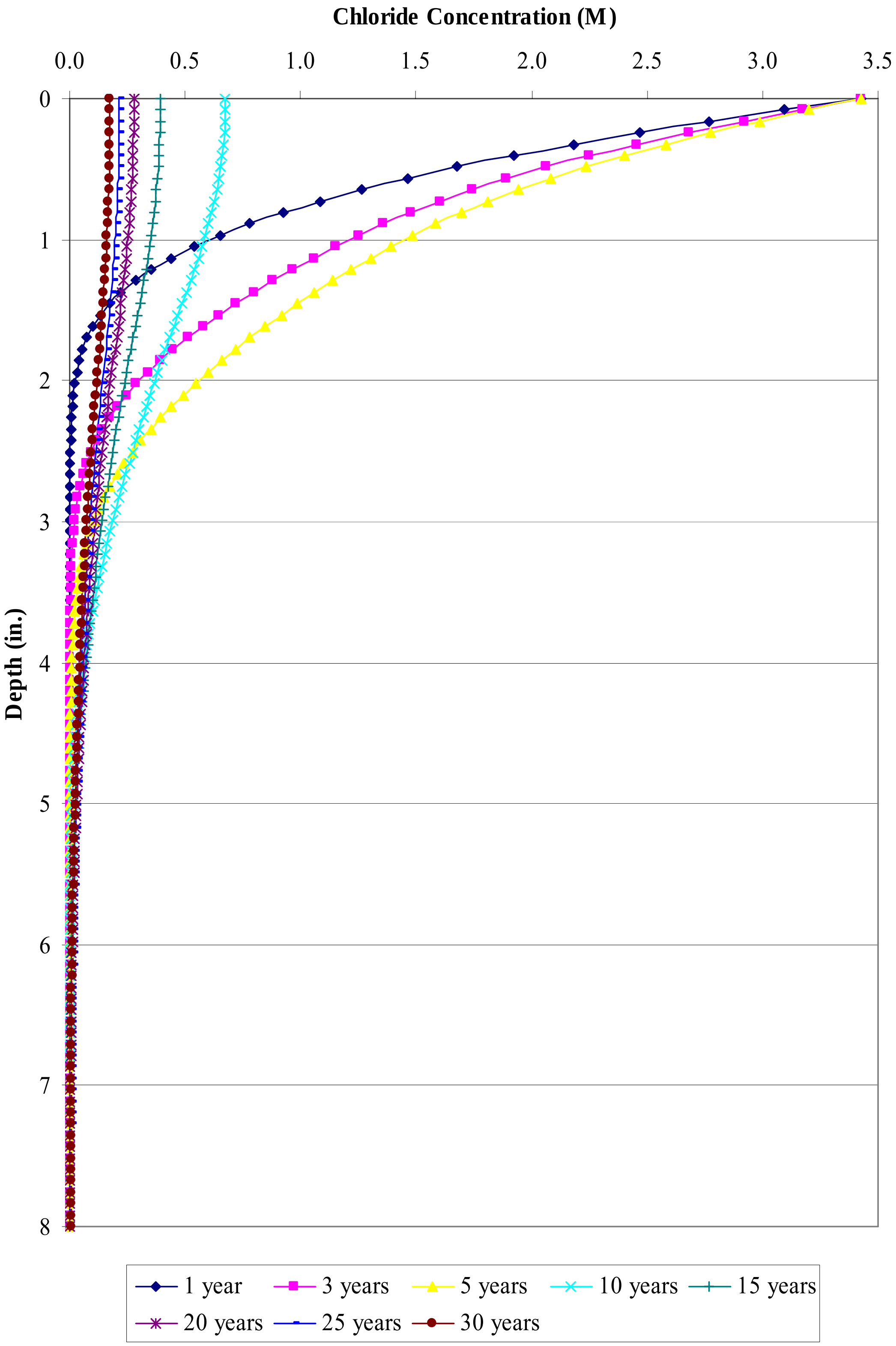

FIGURE A.6 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 5 years.

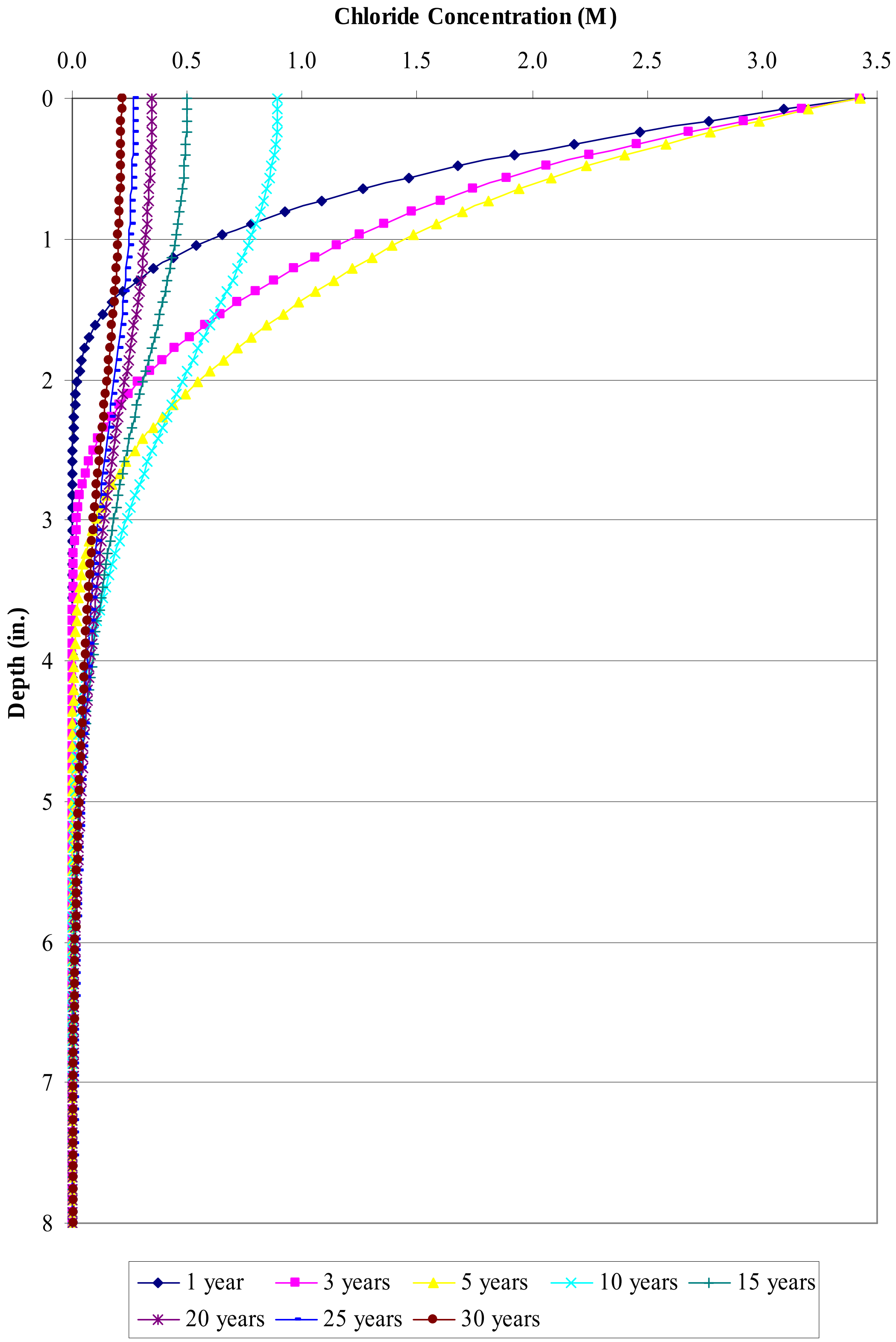

FIGURE A.7 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 6 years.

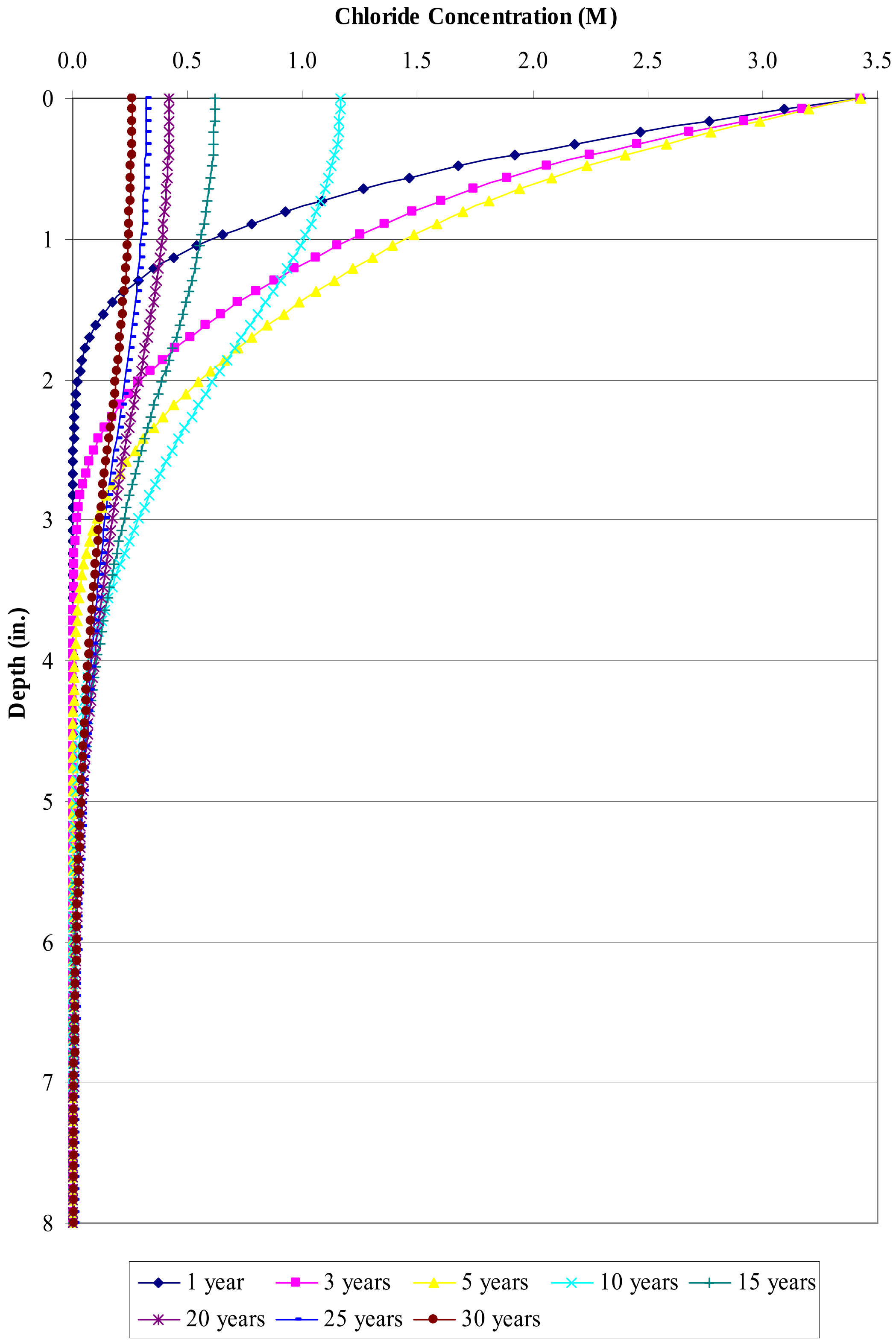

FIGURE A.8 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 7 years.

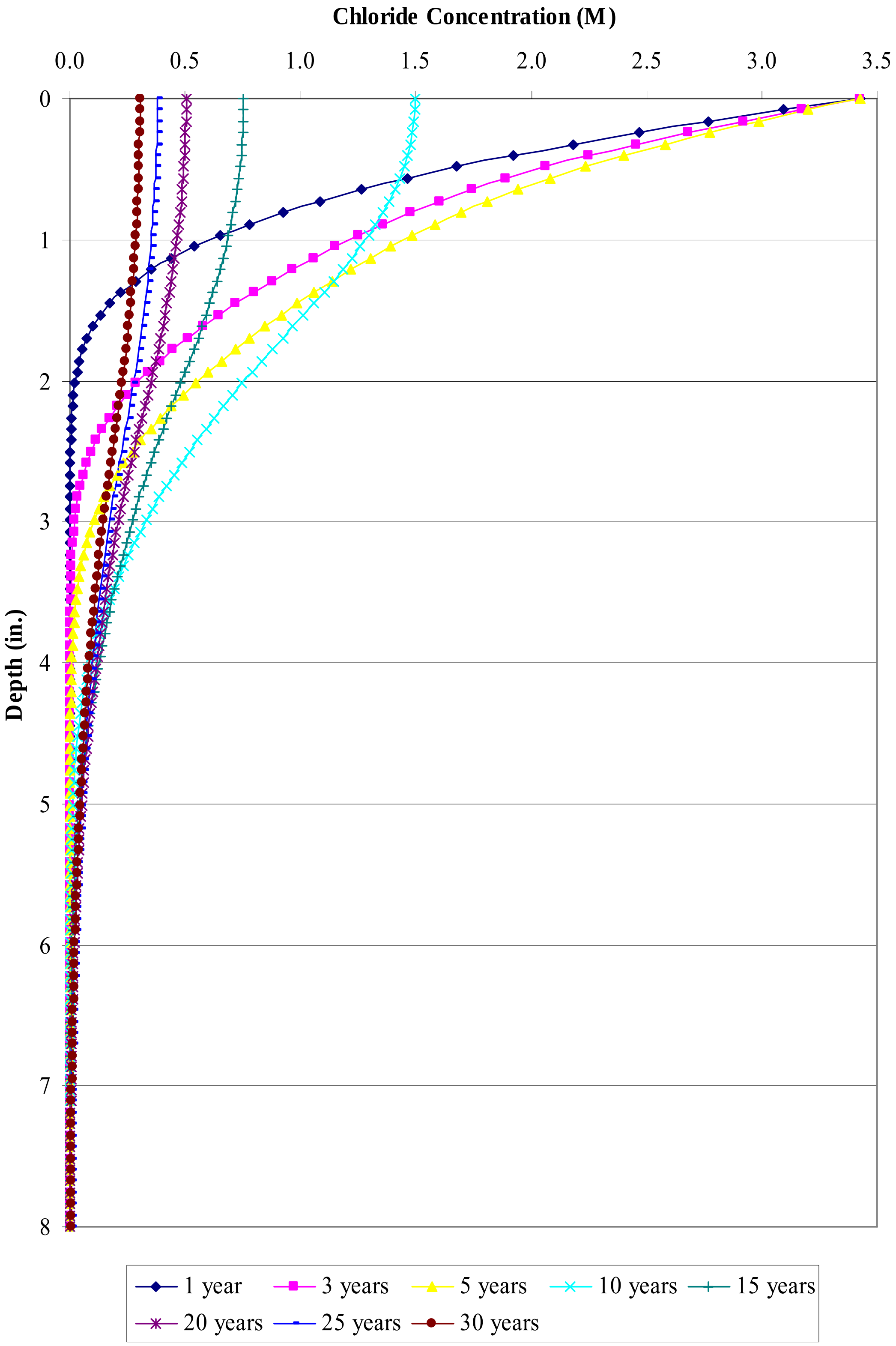

FIGURE A.9 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 8 years.

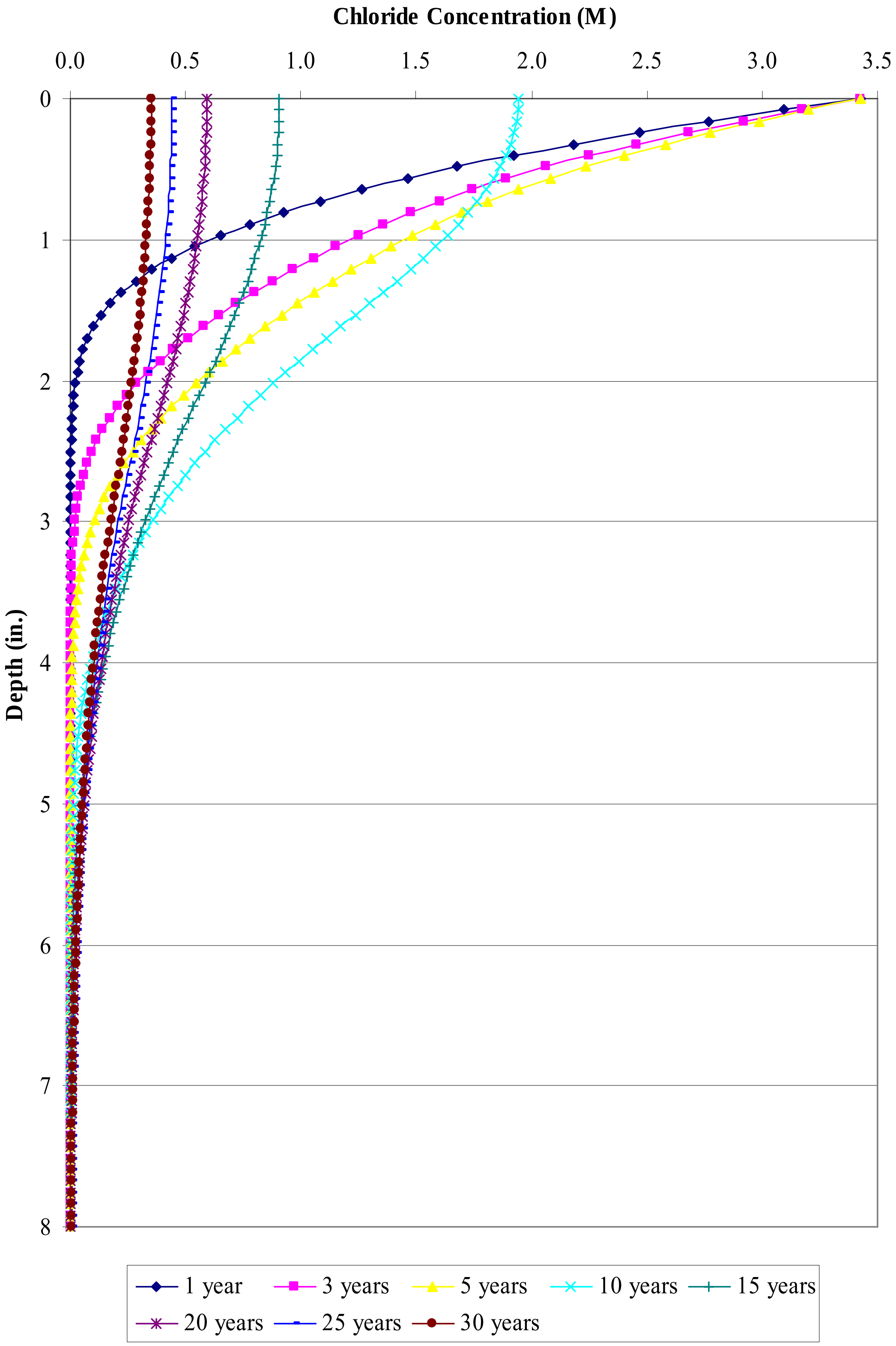

FIGURE A.10 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 9 years.

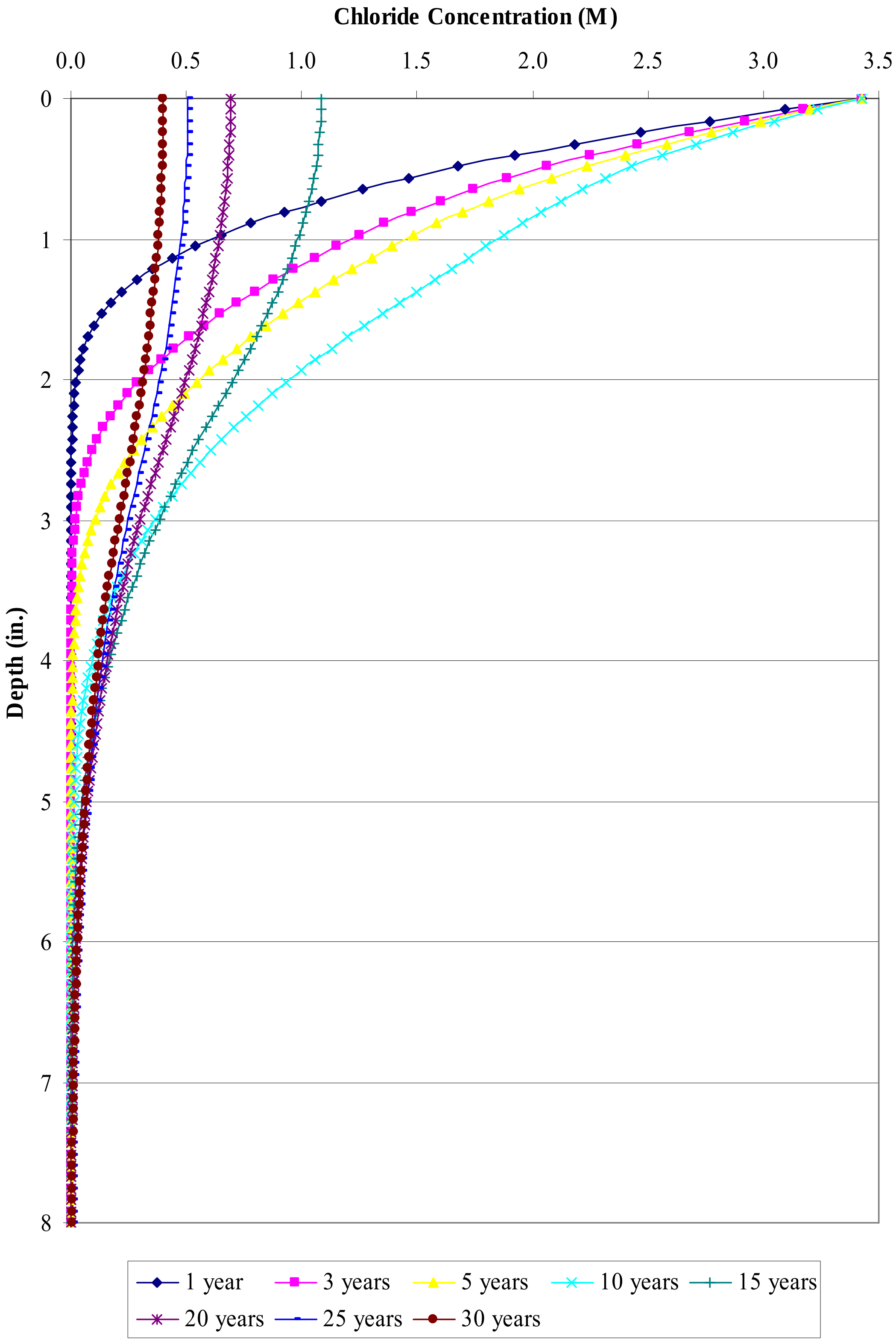

FIGURE A.11 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 10 years.

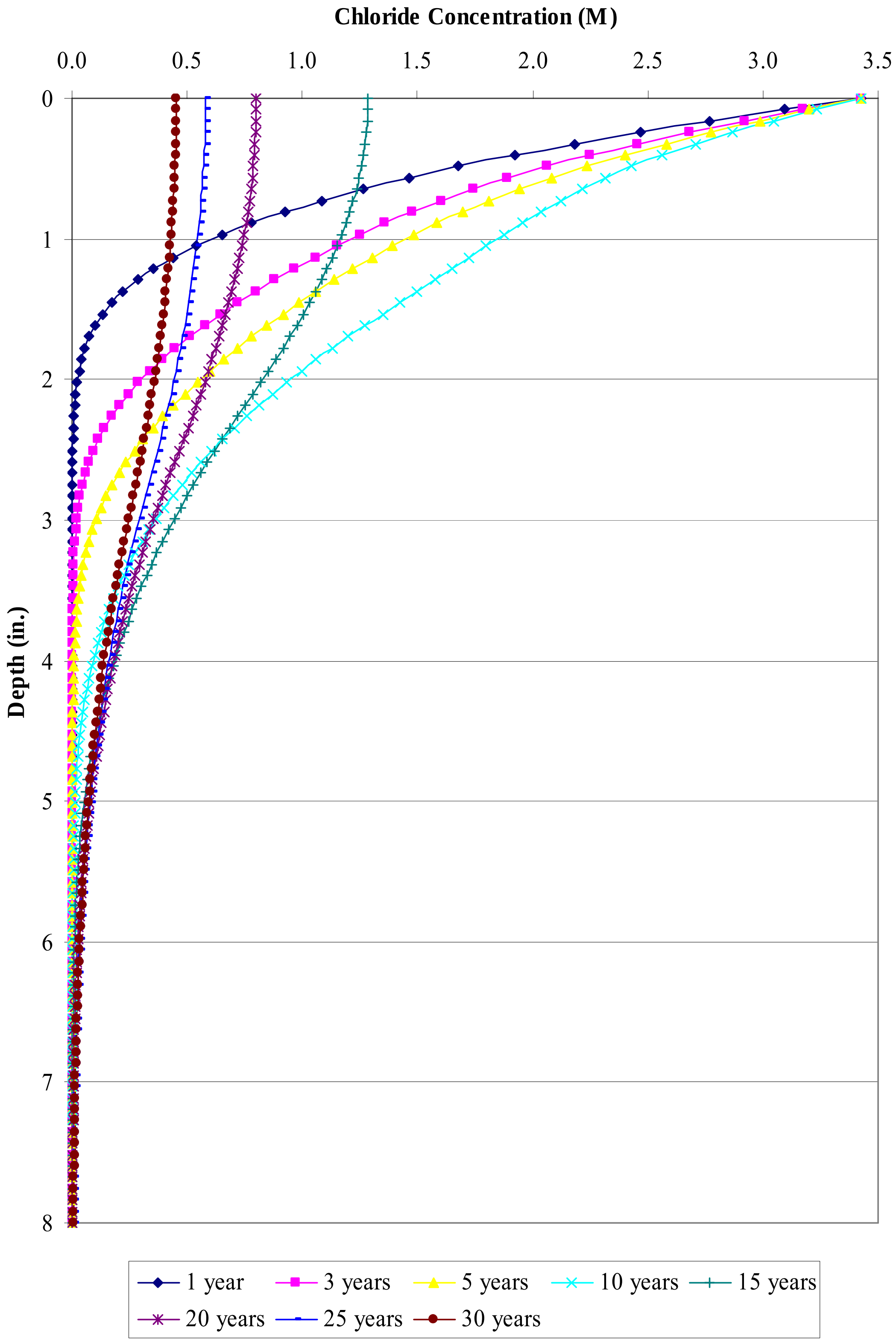

FIGURE A.12 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 11 years.

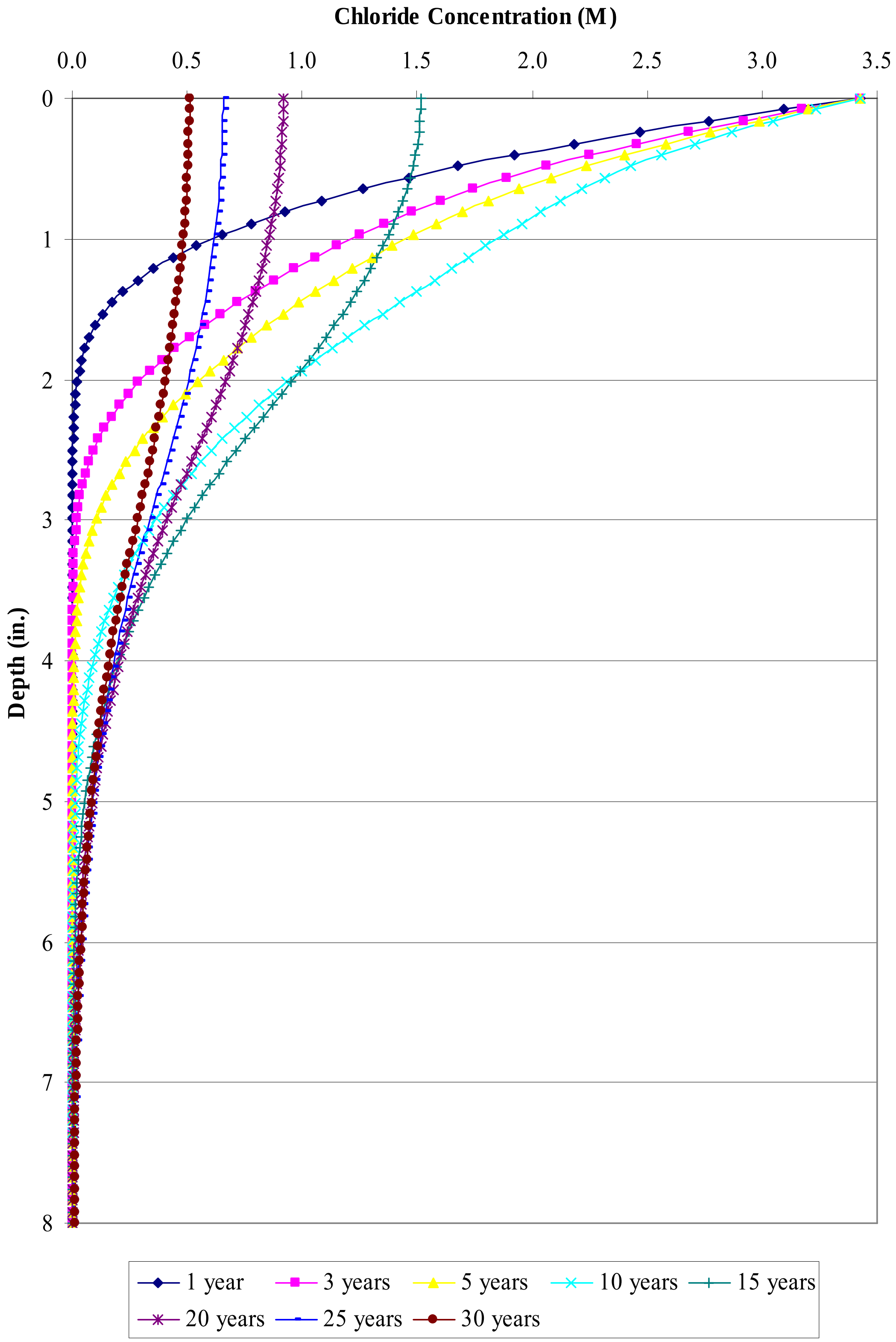

FIGURE A.13 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 12 years.

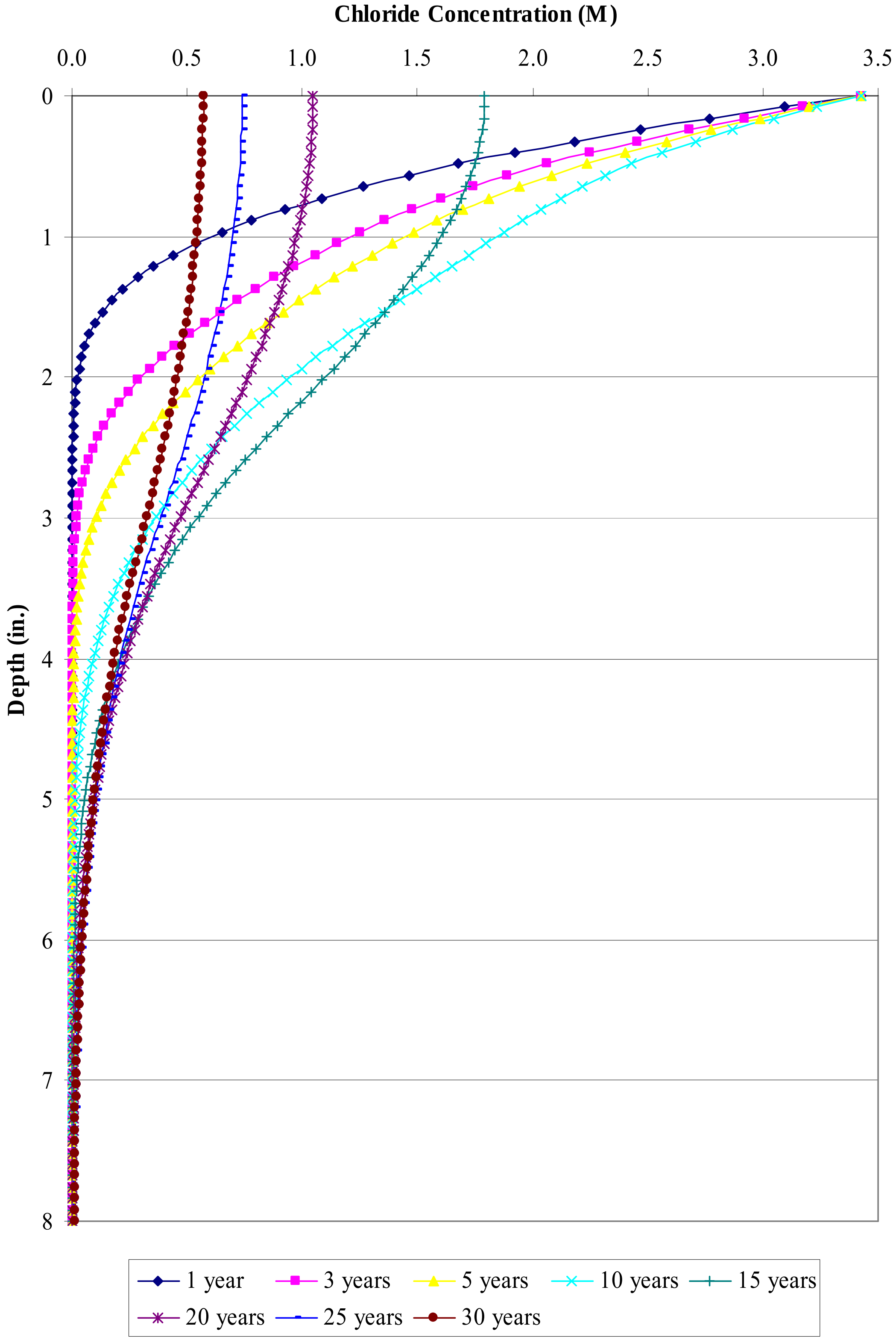

FIGURE A.14 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 13 years.

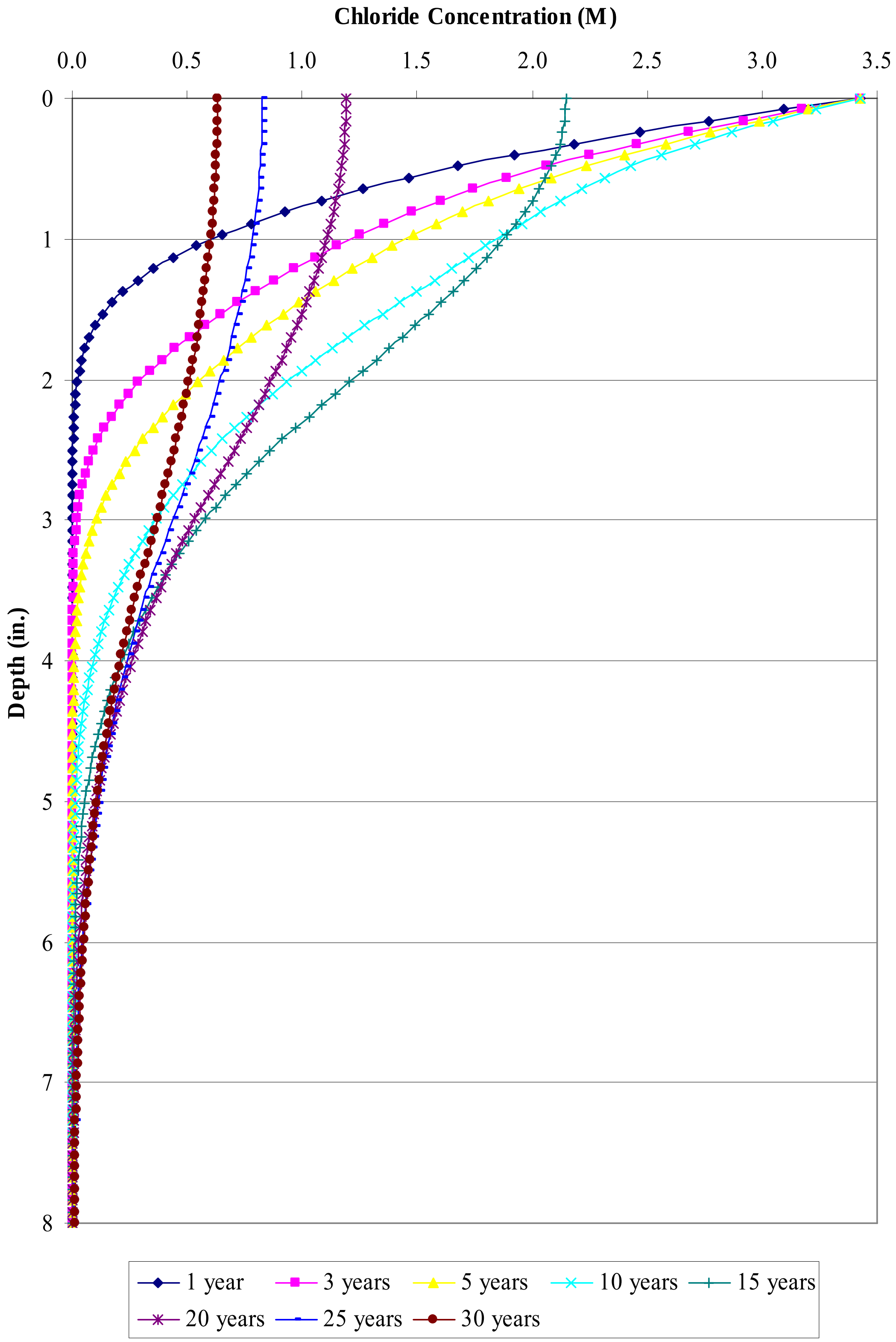

FIGURE A.15 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 14 years.

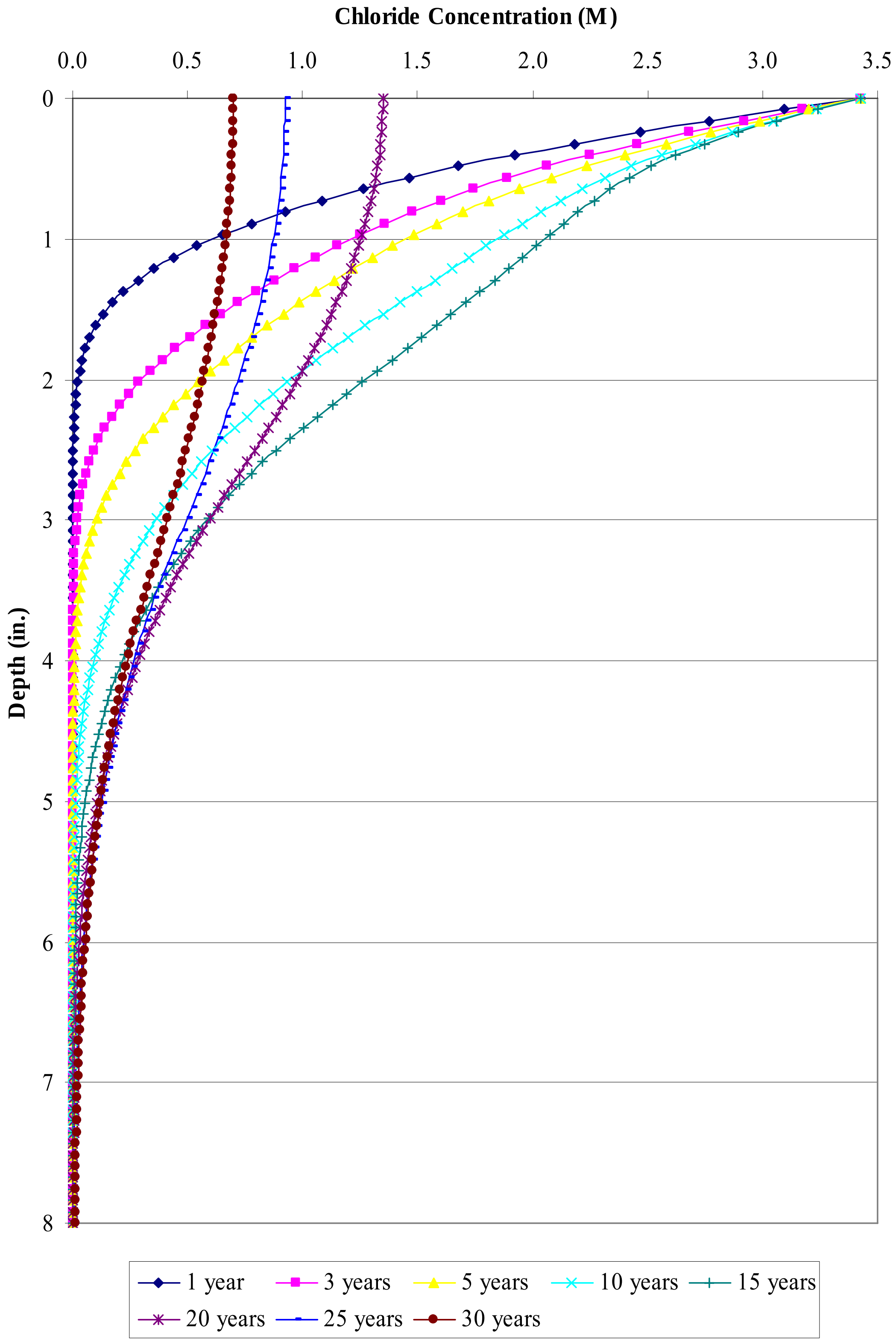

FIGURE A.16 Chloride concentrations of decks with SIPMFs with a surface treatment applied at 15 years.

APPENDIX B:

CHLORIDE CONCENTRATIONS OF DECKS WITHOUT SIPMFS

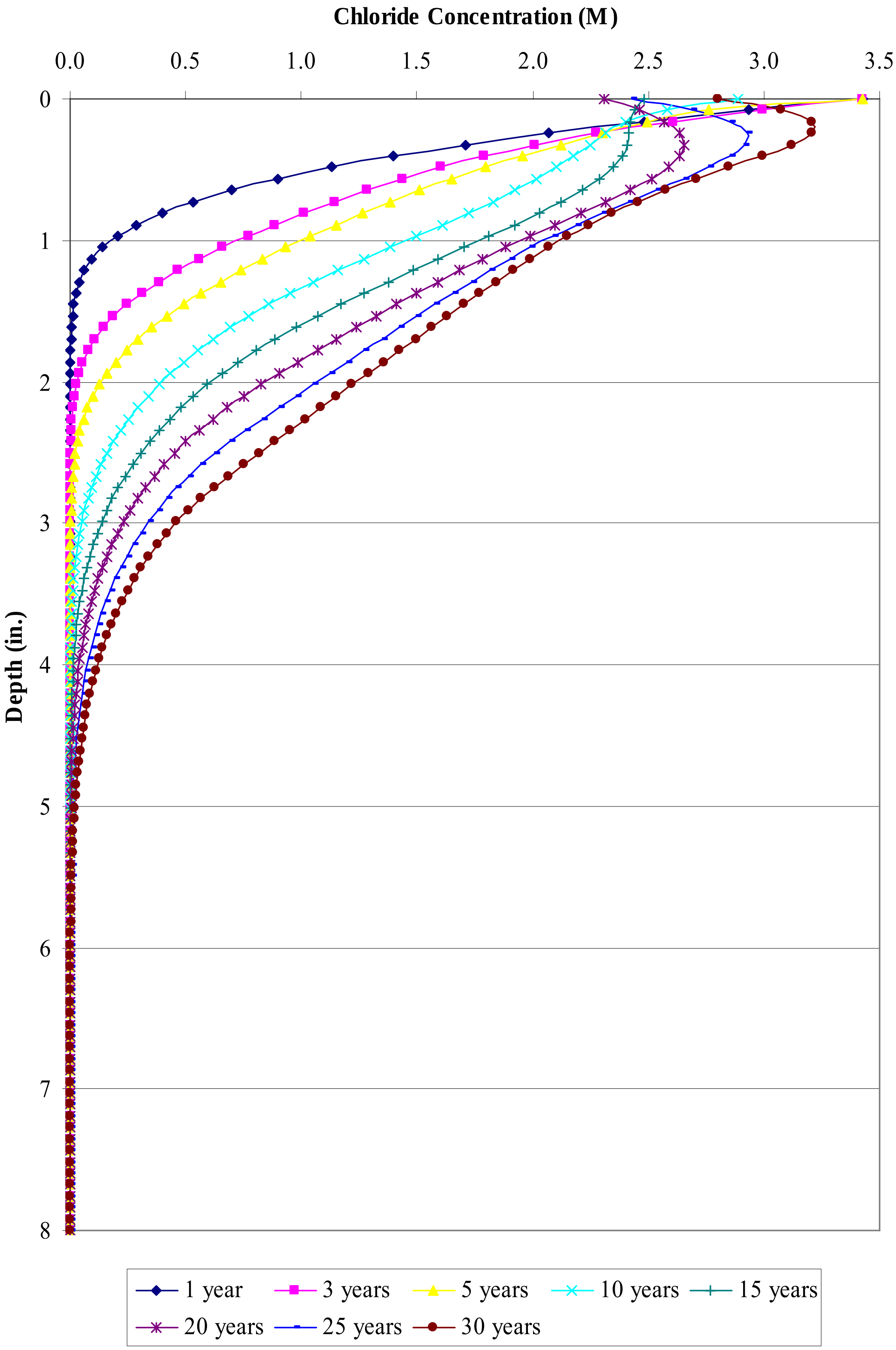

FIGURE B.1 Chloride concentrations of decks without SIPMFs with no surface treatment applied.

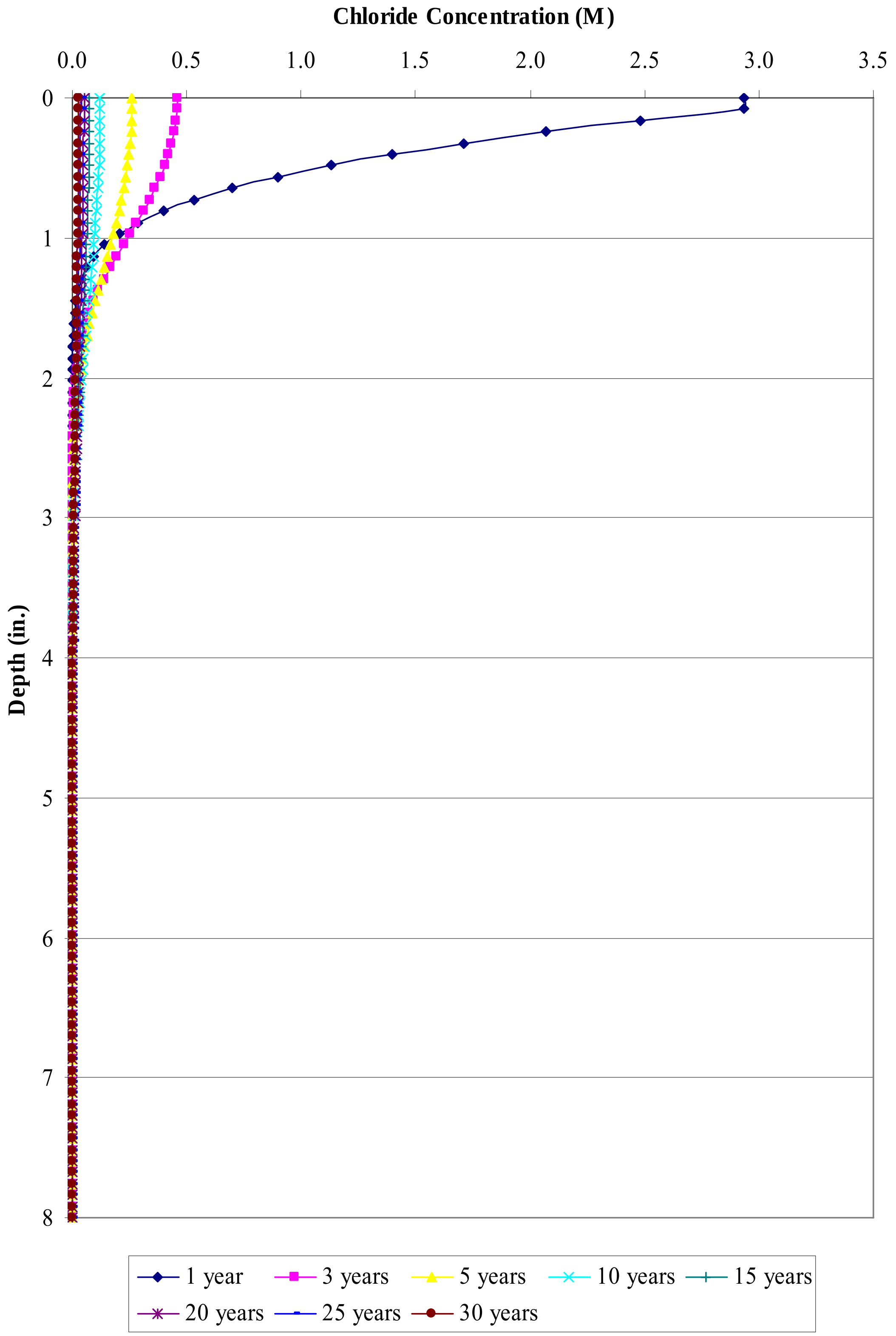

FIGURE B.2 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 1 year.

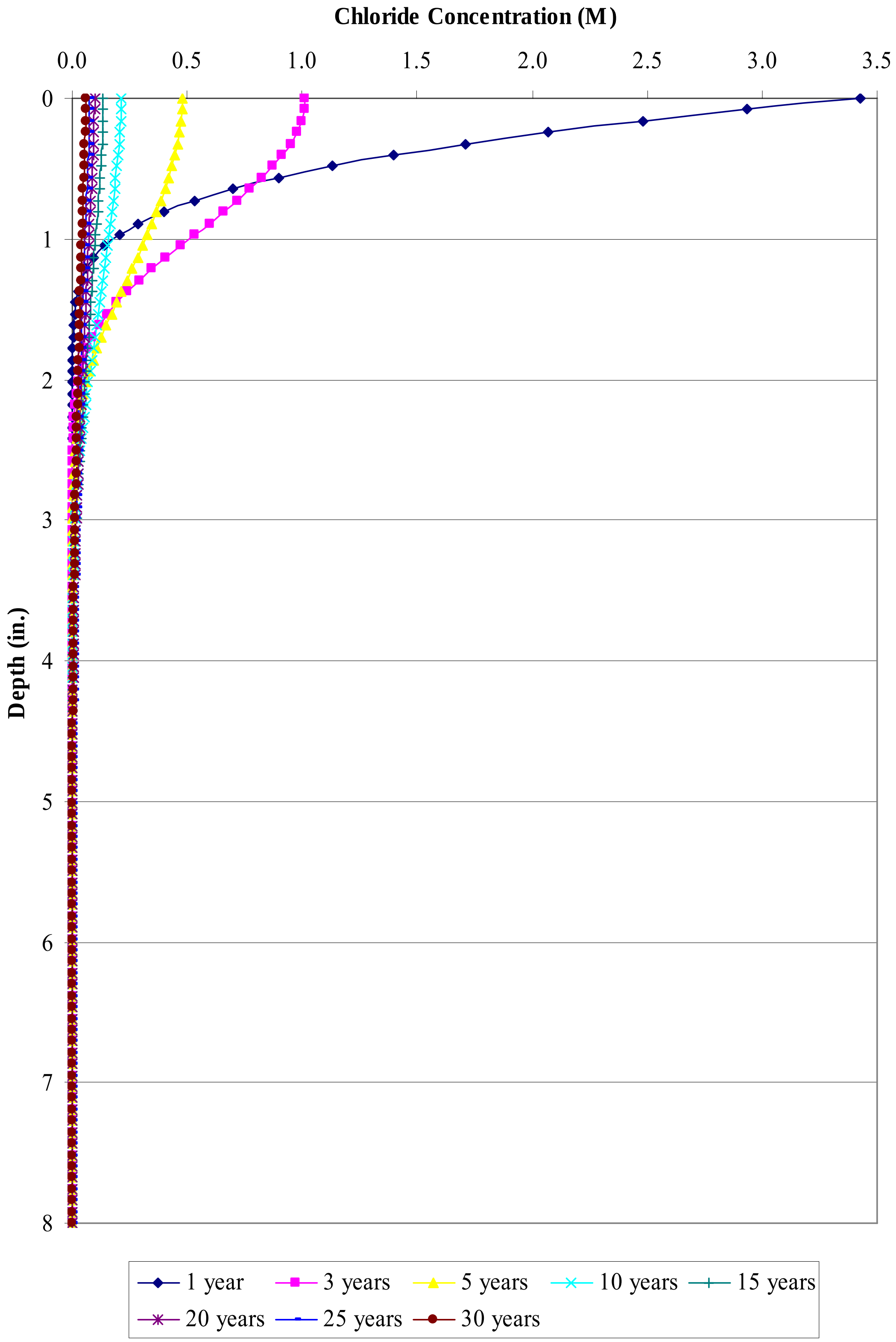

FIGURE B.3 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 2 years.

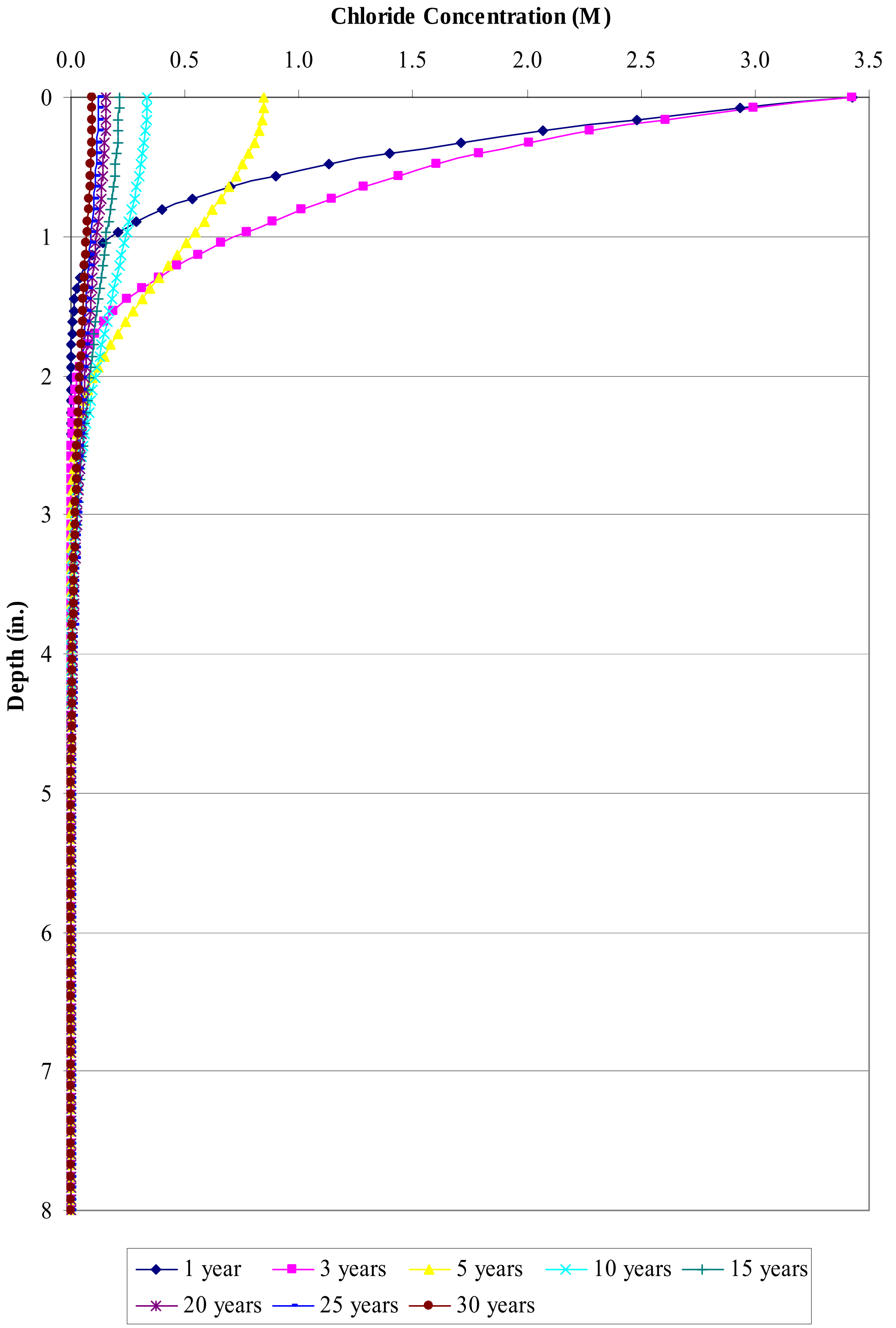

FIGURE B.4 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 3 years.

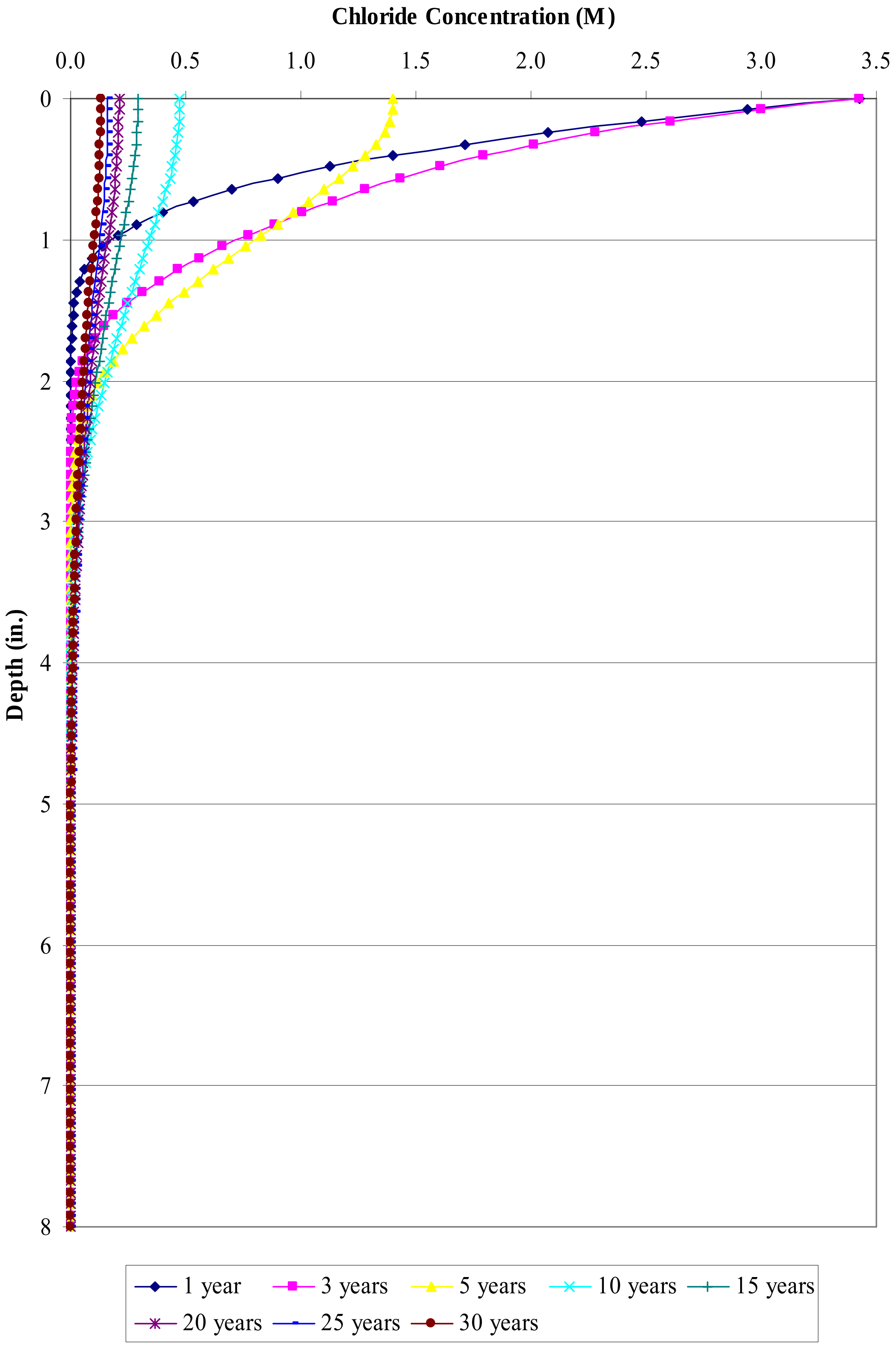

FIGURE B.5 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 4 years.

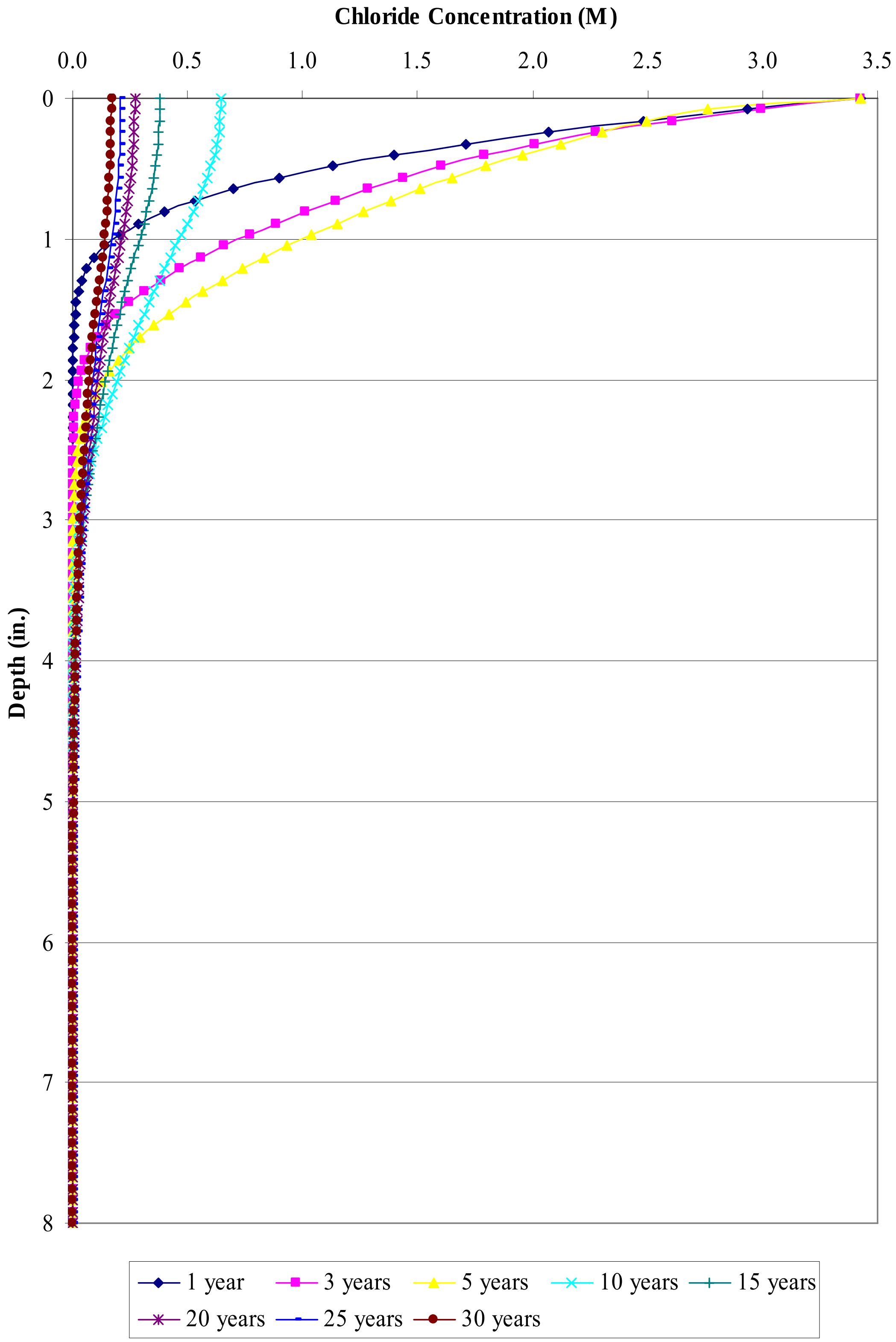

FIGURE B.6 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 5 years.

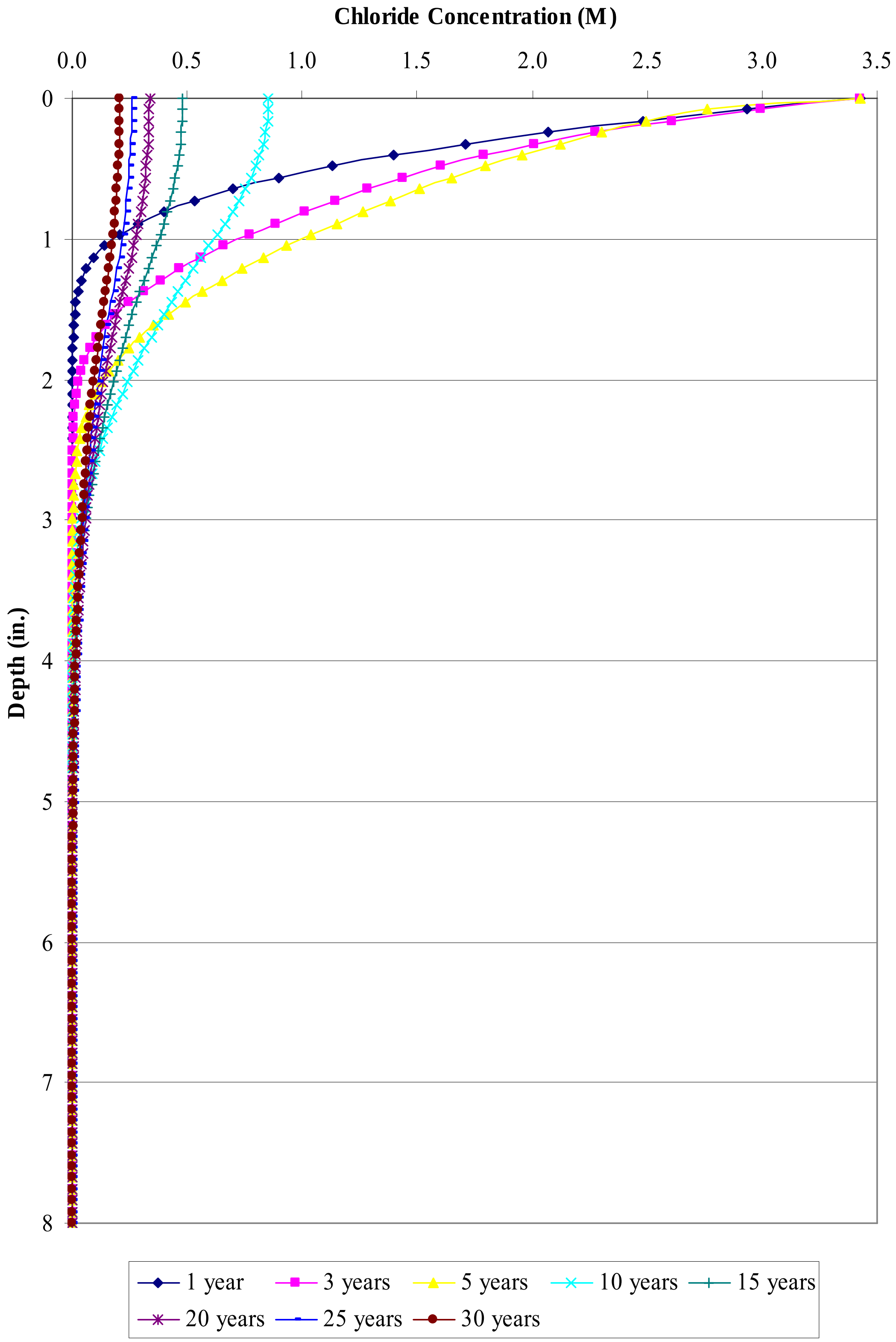

FIGURE B.7 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 6 years.

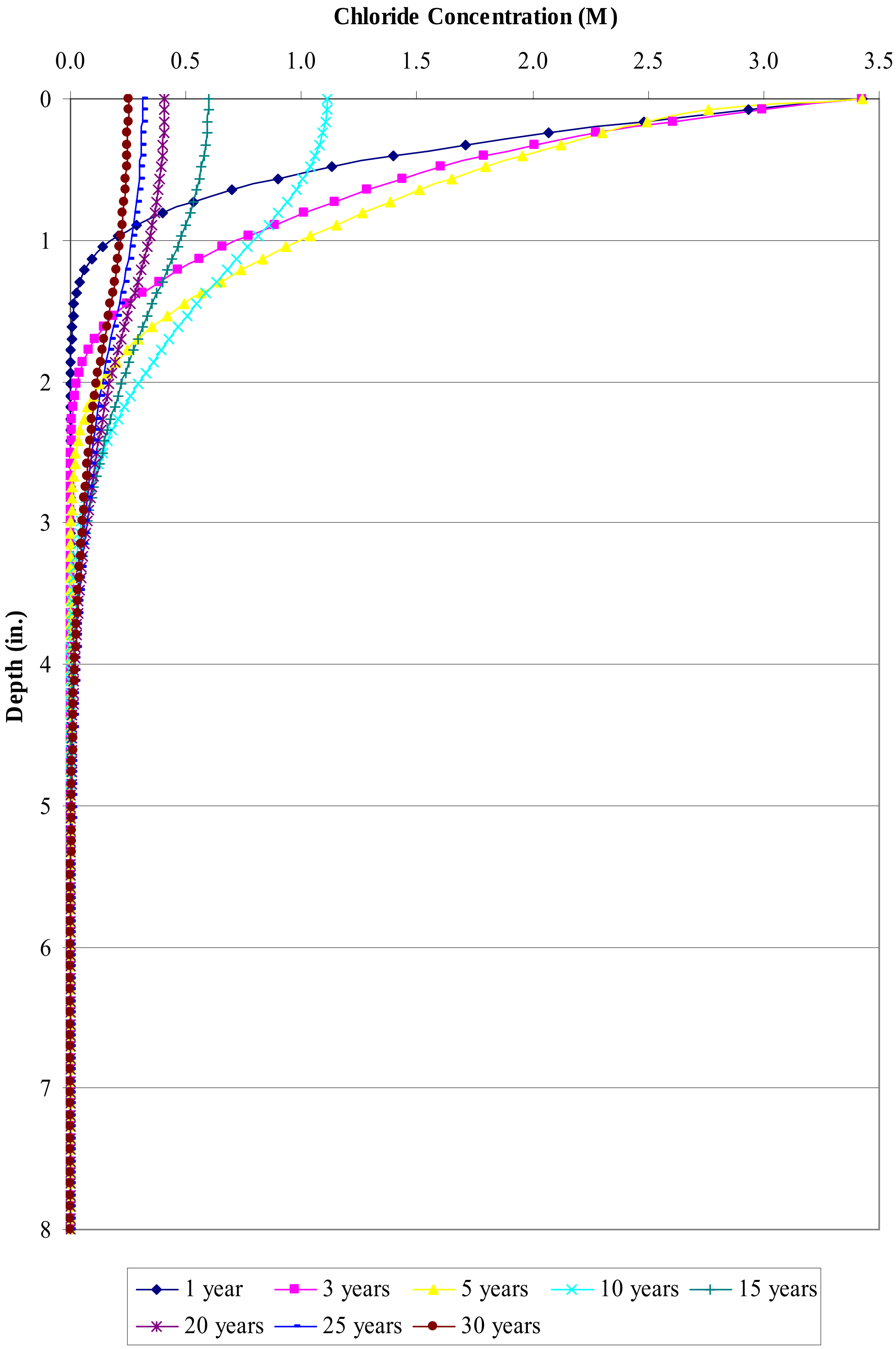

FIGURE B.8 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 7 years.

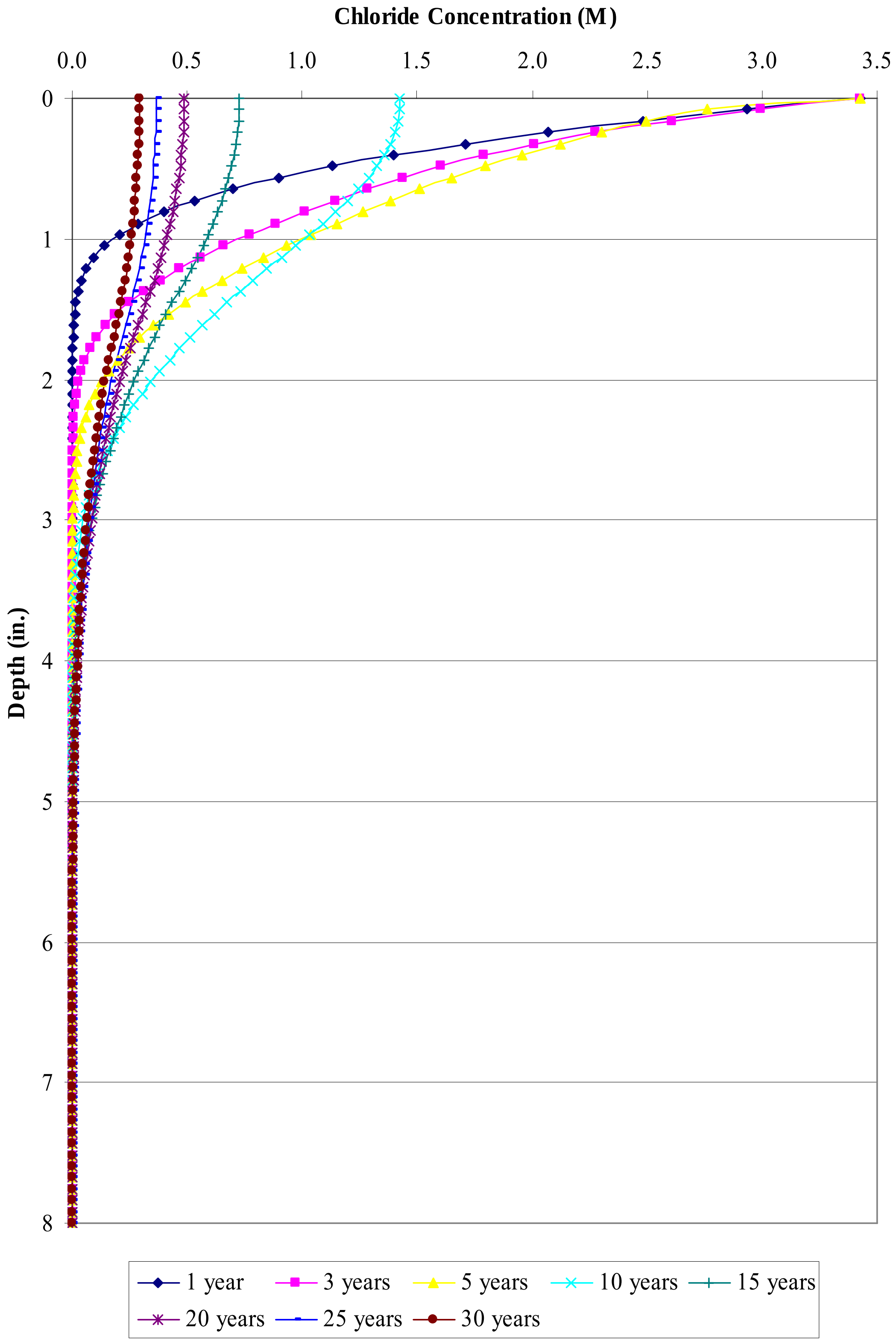

FIGURE B.9 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 8 years.

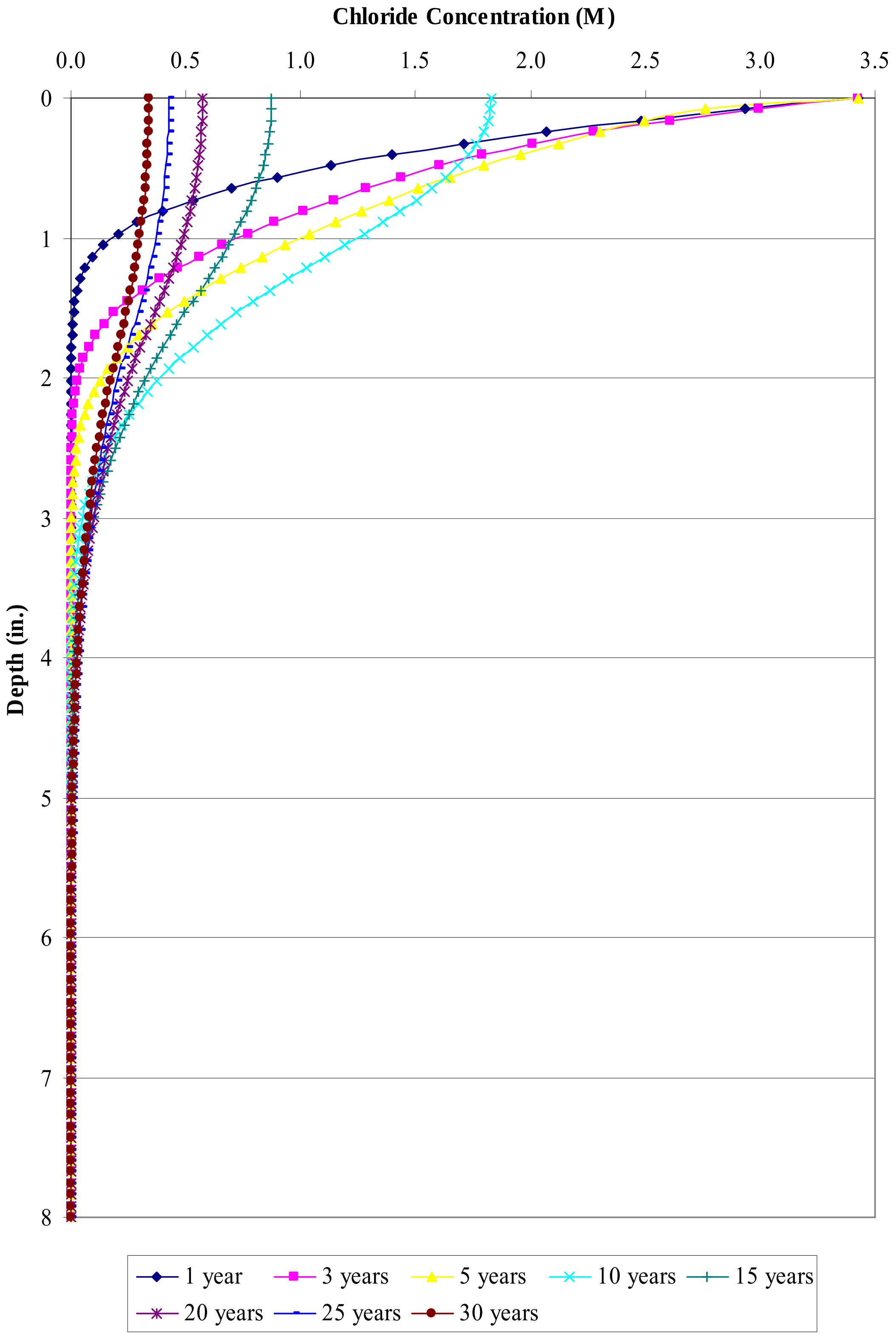

FIGURE B.10 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 9 years.

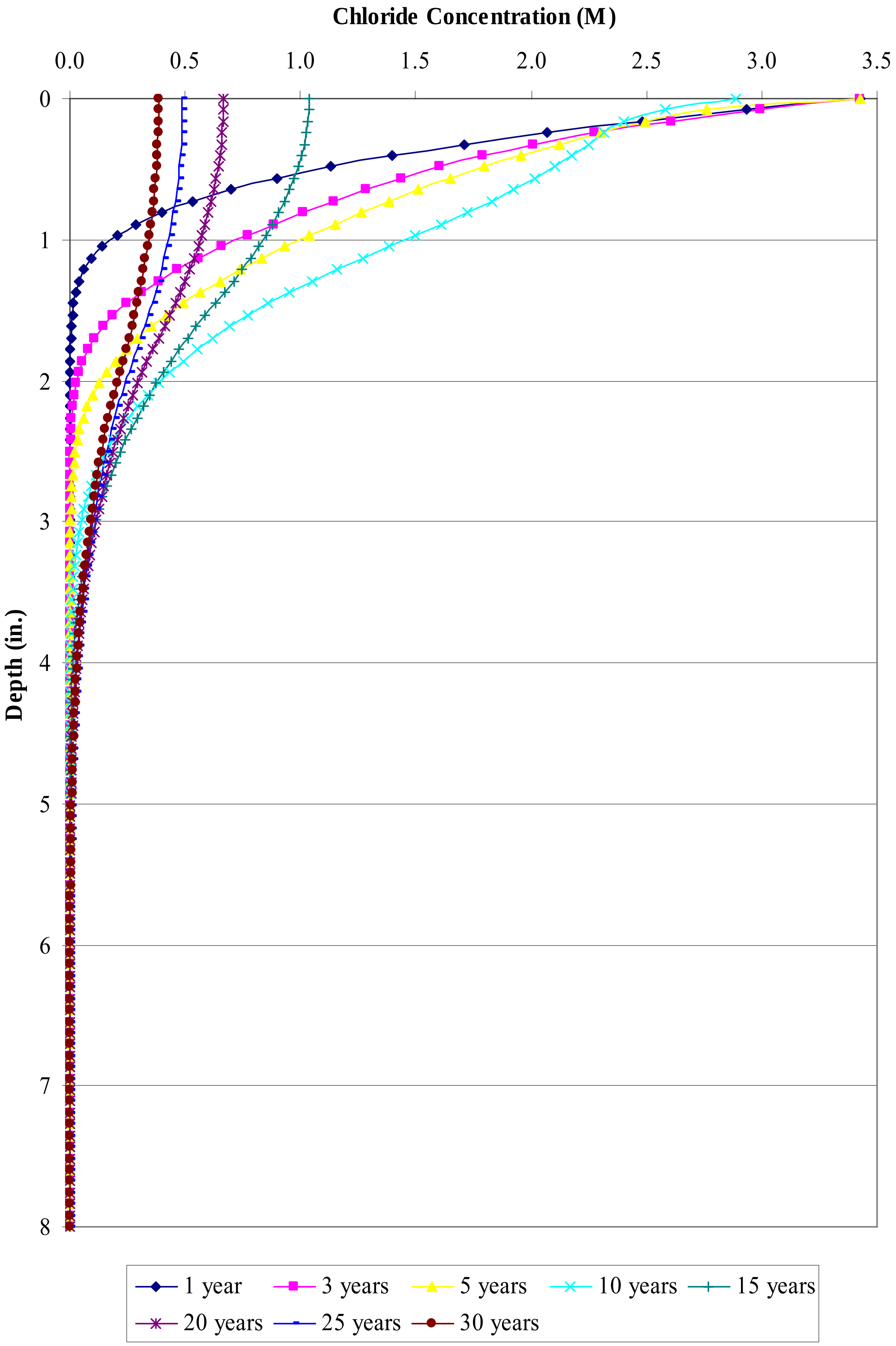

FIGURE B.11 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 10 years.

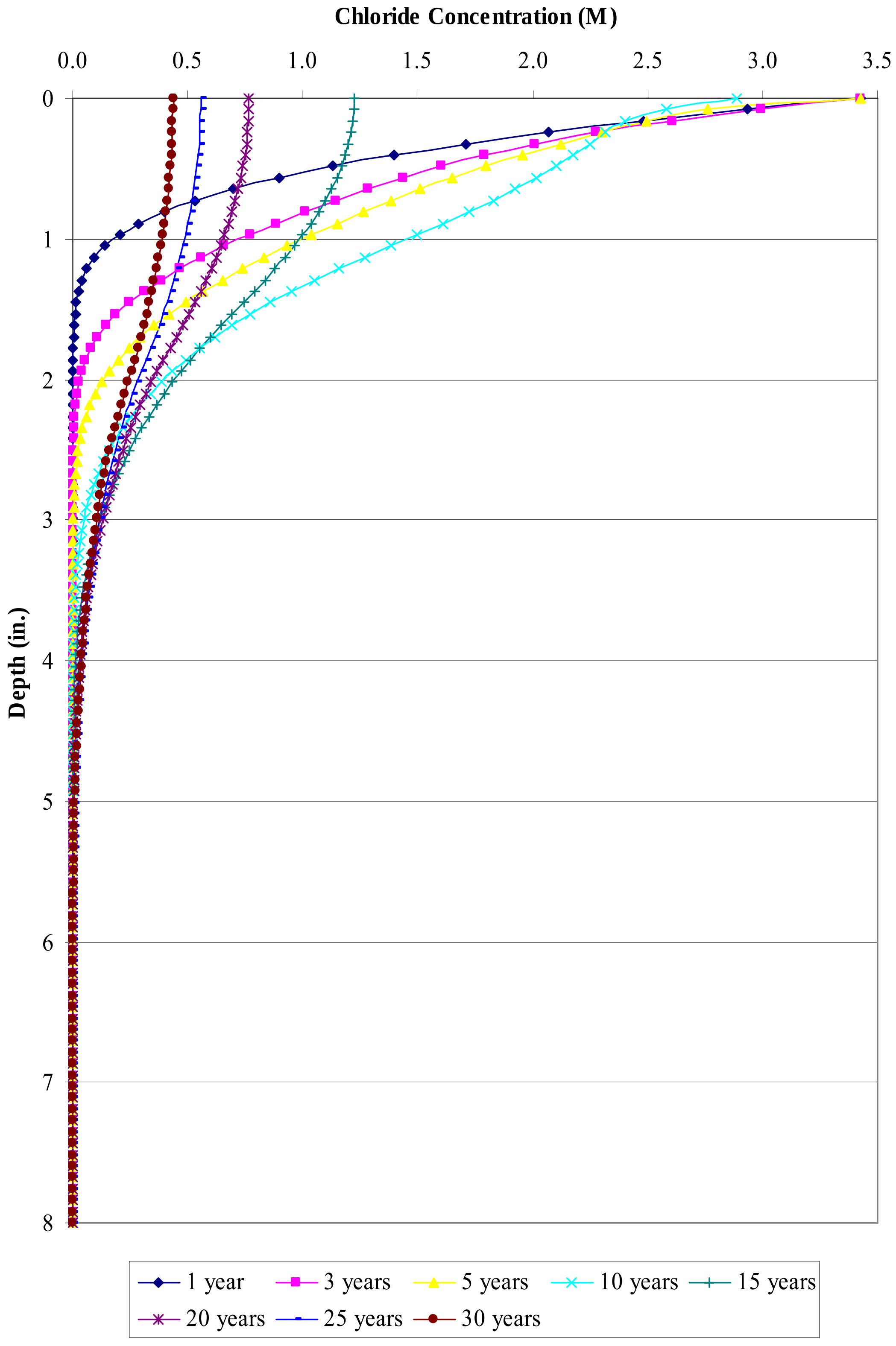

FIGURE B.12 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 11 years.

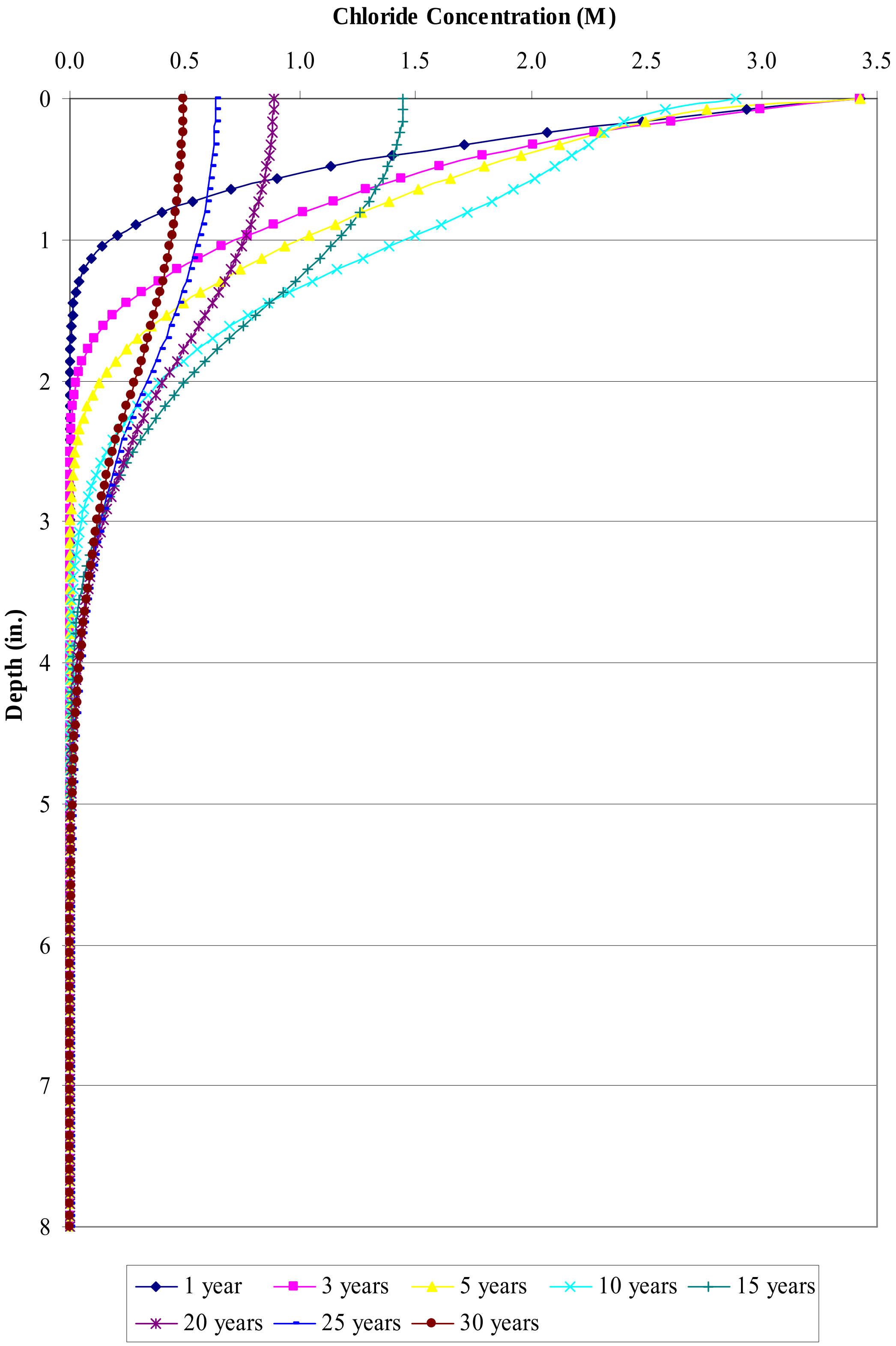

FIGURE B.13 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 12 years.

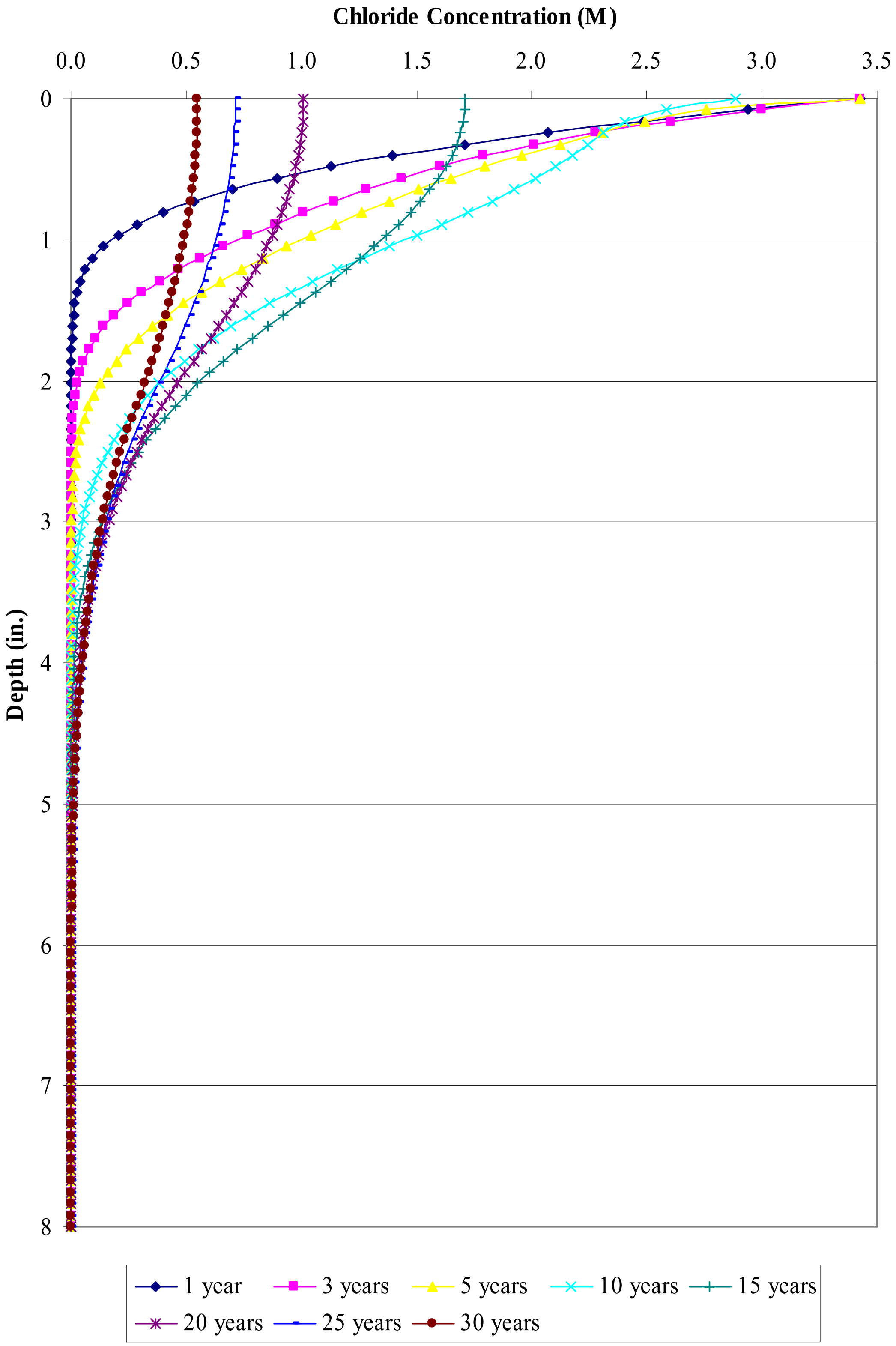

FIGURE B.14 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 13 years.

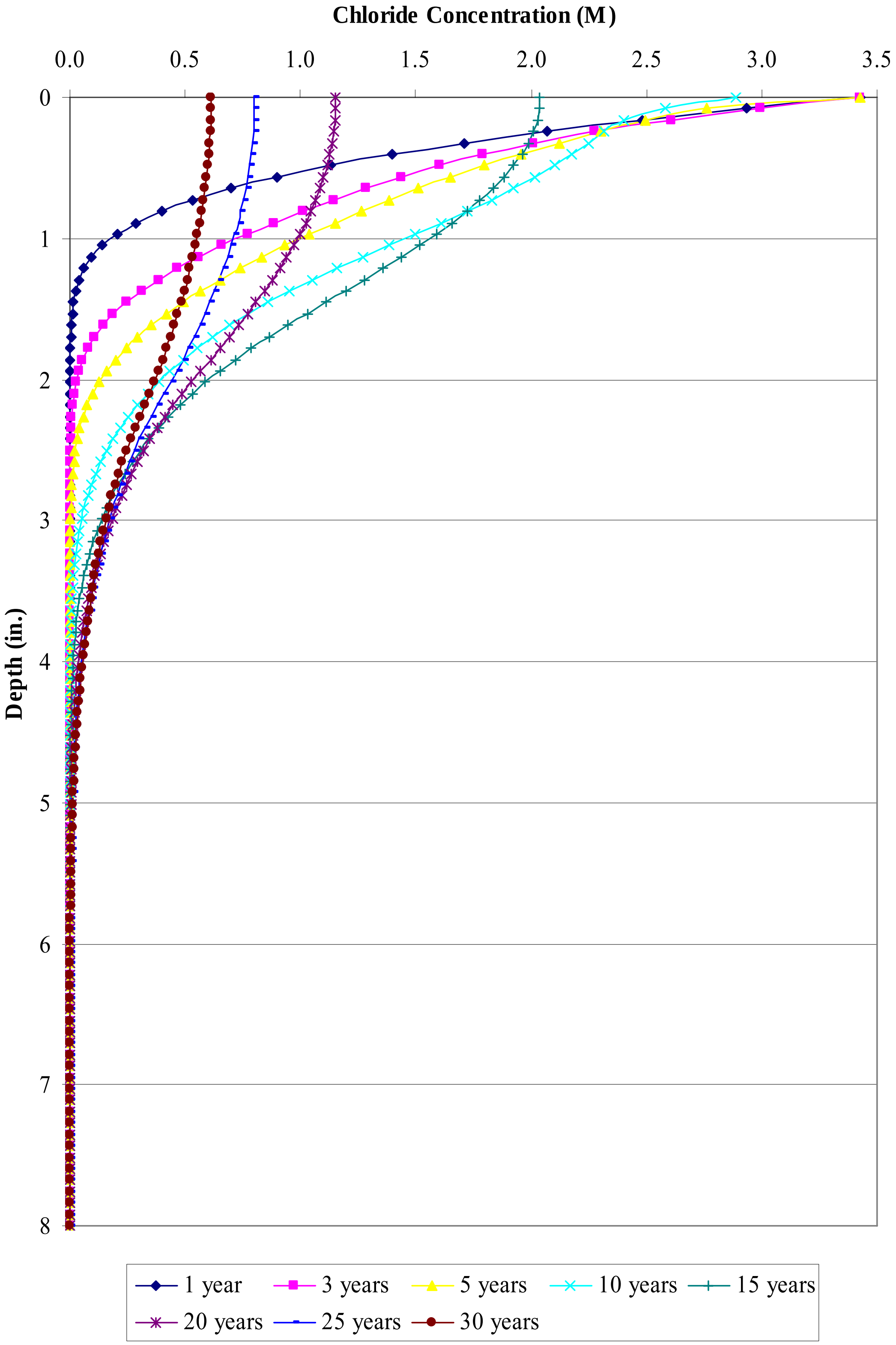

FIGURE B.15 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 14 years.

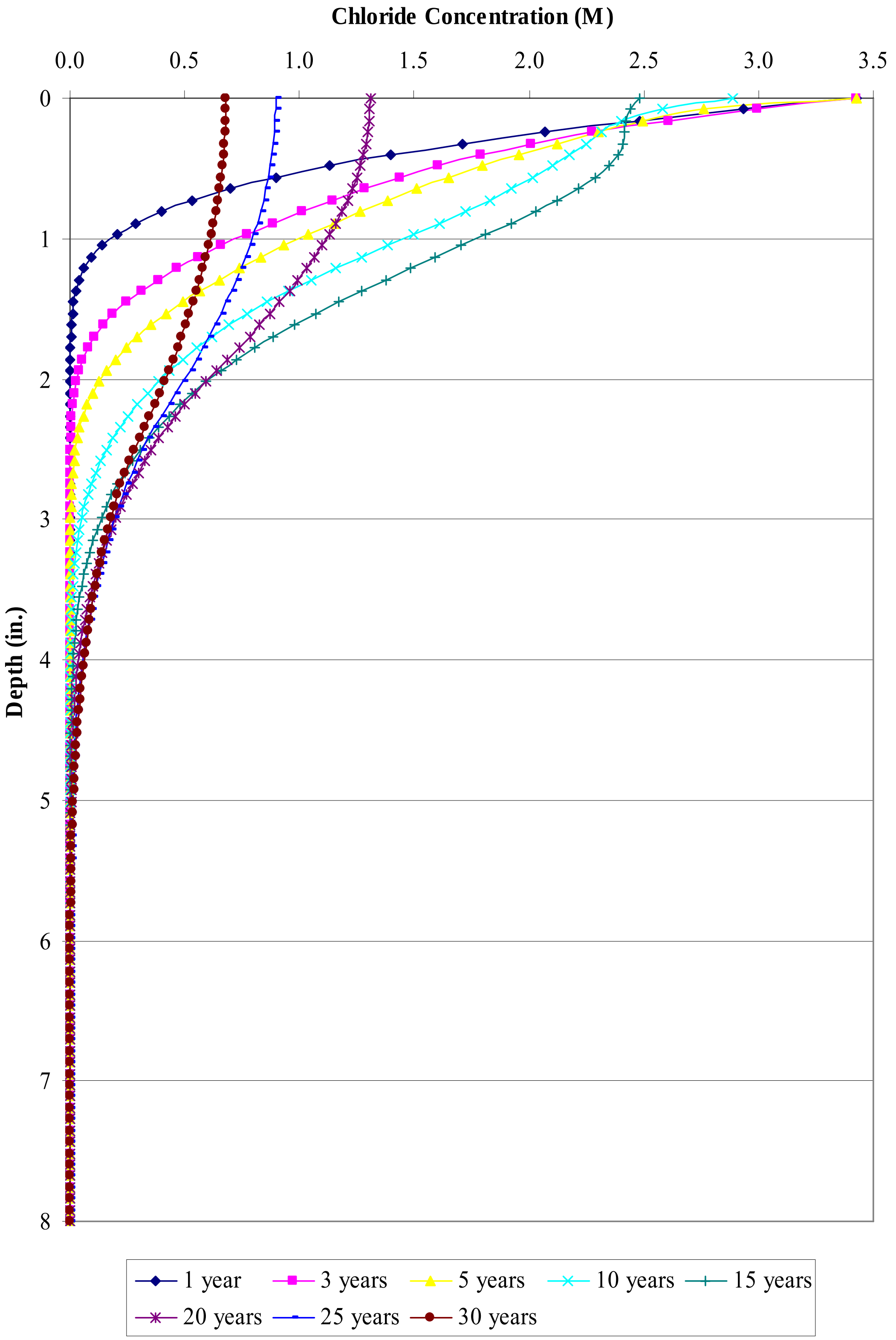

FIGURE B.16 Chloride concentrations of decks without SIPMFs with a surface treatment applied at 15 years.