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Curtis Daniel Nolan
Brigham Young University - Provo

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EFFECT OF INITIAL SCARIFICATION AND OVERLAY TREATMENT TIMING ON CHLORIDE CONCENTRATIONS IN CONCRETE BRIDGE DECKS

by

Curtis Daniel Nolan

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GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Curtis Daniel Nolan

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

Date	W. Spencer Guthrie, Chair
Date	Mitsuru Saito
Date	Gustavious P. Williams

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Date

W. Spencer Guthrie
Chair, Graduate Committee

Accepted for the Department

E. James Nelson
Graduate Coordinator

Accepted for the College

Alan R. Parkinson
Dean, Ira A. Fulton College of Engineering and Technology

ABSTRACT

EFFECT OF INITIAL SCARIFICATION AND OVERLAY TREATMENT TIMING ON CHLORIDE CONCENTRATIONS IN CONCRETE BRIDGE DECKS

Curtis Daniel Nolan
Department of Civil and Environmental Engineering
Master of Science

Considering the pervasive presence of chlorides in concrete bridge decks, bridge engineers have a critical responsibility to perform proper and effective preventive maintenance and rehabilitation operations. Bridge engineers often perform scarification and overlay (SO) procedures on concrete bridge decks to minimize the corrosion of reinforcing steel due to chloride ingress. Given the need to develop guidelines for the initial timing of SO treatments, the specific objectives of this research were to collect information from several department of transportation (DOT) personnel about their SO procedures and, subsequently, to determine the recommended timing of initial SO procedures on concrete bridge decks for preventing the accumulation of corrosion-inducing levels of chlorides and extending deck service life.

A questionnaire survey of state DOTs was conducted, and numerical modeling of SO treatments was performed. Simulations involving both decks with and without stay-in-place metal forms (SIPMFs) were performed. Numerical modeling was performed

for each unique combination of variables through a service life of 50 years to determine the recommended initial timing of SO treatment in each case.

The research results show that, overall, bridge decks without SIPMFs can endure longer delays in SO treatment timing than those with SIPMFs; in all cases, the absence of SIPMFs extended the amount of time before an SO treatment was needed. For decks with SIPMFs, the allowable delay in SO timing ranged from 2 to 6 years, while on decks without SIPMFs the allowable delay in SO timing ranged from 6 to 18 years. These delays are only 1 to 3 years longer than allowable delays associated with placement of surface treatments investigated in previous research.

On average, the period of additional delay allowed before an SO treatment is required in decks with SIPMFs was 2 years with each additional 0.5 in. of OCD. In decks without SIPMFs, the presence of a greater OCD had a more pronounced effect on the latest recommended timing of treatment than in the decks with SIPMFs; an average additional delay period of 5 years was obtained with each additional 0.5 in. of OCD in decks without SIPMFs.

Together with the findings of this research and the specific properties of the bridge deck under scrutiny, engineers can determine the appropriate timing of rehabilitation procedures to prevent or mitigate corrosion of the steel reinforcement of a bridge deck and ensure the usability of the deck for its intended service life. Although the conditions studied in this research were consistent with bridges located in the state of Utah, bridge decks that exist in similar environments and that are subjected to similar treatments of deicing salts as part of winter maintenance could exhibit similar properties to the decks simulated in this research. Engineers should carefully consider the results of this research and implement proper timing of SO treatments on their respective bridge decks to protect against and minimize the effects of corrosion due to chloride ingress.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Corrosion of reinforcing steel due to chloride ingress is a leading cause of deterioration of the nation's bridge infrastructure (*1, 2, 3, 4, 5*). Rust, the byproduct of corrosion, is up to 600 percent more voluminous than its parent materials (*6*). The formation of rust causes tensile stresses in concrete bridge decks and leads to cracking and delamination. These distresses result in eventual weakening and even failure of affected structures. Concrete bridge decks located in coastal climates and areas where deicing salts are used as a form of winter road maintenance are especially vulnerable to accelerated corrosion due to the presence of chlorides. The typical threshold value for corrosion potential of reinforcing steel in concrete is 2 lb of chloride per cubic yard of concrete (*7*).

In a 2004 questionnaire survey conducted of bridge engineers and managers at 39 state departments of transportation (DOTs) nationwide, Brigham Young University (BYU) researchers inquired about decision thresholds utilized to determine if a bridge deck was in need of rehabilitation or replacement (*7*). The respondents indicated that action was needed if the deck was more than 20 to 50 percent deteriorated, with the wide range in values being associated with the different methods by which deterioration can be assessed. Most respondents indicated the use of visual inspection, chaining, coring, chloride concentration testing, and/or half-cell potential testing for deck evaluations (*7*). As evidenced in the survey results, the assessment strategies for concrete bridge decks differ markedly among the different DOTs. When action is warranted, procedures such as surface treatments, scarification and overlay (SO) treatments, cathodic protection, electrochemical chloride extraction, concrete removal and patching, and complete deck replacement are among those performed (*7, 8*), yet no standard procedure is apparently followed for determining the correct timing of deck rehabilitation.

To this end, however, research performed since the time of the 2004 survey has investigated the latest timing of deck surface treatments allowable before the corrosion threshold of 2 lb of chloride per cubic yard of concrete is exceeded at the level of the reinforcing steel (*9*). Depending on the presence of stay-in-place metal forms (SIPMFs) and concrete cover thickness, the recommended timing for placement of surface treatments ranges from 1 to 15 years for decks similar to those evaluated in the study. As evidenced by these data, surface treatments are only beneficial during comparatively early stages of bridge deck service life. Once the deck age has exceeded the latest possible timing for surface treatments or other preventive maintenance procedures, a form of rehabilitation or reconstruction must be considered.

SO treatments are among the common forms of rehabilitation that can be performed on concrete bridge decks. Even though SO treatments are utilized by many agencies, the literature does not provide specific guidance about the initial timing of SO treatments with respect to preventing the accumulation of critical levels of chlorides at the level of the reinforcing steel in concrete bridge decks (*10*).

Derived from the need to develop guidelines for the initial timing of SO treatments, the specific objectives of this research were to collect information from several DOT personnel about their SO procedures and, subsequently, to determine the recommended timing of initial SO procedures on concrete bridge decks for preventing the accumulation of corrosion-inducing levels of chlorides and extending deck service life.

1.2 SCOPE

Personnel at 40 DOTs were contacted to obtain information regarding their specific SO procedures. This information was used to design realistic simulations of rehabilitation procedures on concrete bridge decks with and without SIPMFs. Computer simulations were performed to investigate the efficacy of treatments placed on decks ranging from 2 to 24 years in age, and, after treatment, chloride concentrations at the level of the reinforcing steel were calculated through 50 years of total bridge deck life.

The concrete decks were modeled with original cover depths (OCDs) of 2.0 in., 2.5 in., and 3.0 in., and scarification depths of 0.5 in., 1.0 in., and 1.5 in. were evaluated in conjunction with overlay thicknesses of 1.5 in. and 2.0 in. All possible combinations of these values were modeled to evaluate the various SO treatment options with respect to preventing accumulations of critical concentrations of chlorides in the vicinity of the reinforcing steel on each of the different deck configurations.

1.3 OUTLINE OF REPORT

This report contains five chapters. Chapter 1 presents the objectives and scope of the research. Chapter 2 provides information regarding concrete diffusion, the use of SIPMFs on concrete bridge decks, and the construction procedures associated with SO treatments. Descriptions of the questionnaire survey and numerical modeling are given in Chapter 3. Test results are explained in Chapter 4 with a discussion of the research findings with respect to rehabilitation procedures. Also, a comparison between the results of the current research and those of previous studies on timing of surface treatments is provided. In Chapter 5, summaries of the procedures, research findings, and recommendations are presented.

CHAPTER 2
BACKGROUND

2.1 OVERVIEW

The following sections discuss the diffusion of chlorides in concrete, the effect of SIPMFs on chloride intrusion in concrete bridge decks, and the basic SO procedure on bridge decks in regards to concrete removal, overlay placement, and costs.

2.2 CHLORIDE DIFFUSION

In this research, chloride ions are presumed to enter concrete bridge decks primarily through diffusion, a process in which the ions travel through the pore water that exists within concrete. Diffusion of chloride ions in concrete is generally believed to follow Fick's second law of diffusion (*1, 11*). Diffusion begins when chloride solutions first contact the concrete surface (*5*). The rate at which these ions penetrate concrete is strongly influenced by the concentration gradient of chloride ions in the concrete and the diffusion coefficient of the concrete (*11, 12*). The diffusion coefficient in concrete is controlled by the water-to-cementitious materials ratio of the concrete mix, tortuosity and degree of saturation of the pore structure, degree of hydration of the concrete, and external environmental factors (*3, 13*).

The water-cementitious materials ratio plays a significant role in not only the design of a concrete mix, but also the pore structure of the concrete after placement. As the water-cementitious materials ratio of a concrete mix increases, both the porosity of the paste and the permeability of the concrete increase (*14*). In the literature, results from laboratory tests performed on concrete slabs in salt-laden environments indicate that increasing water-cement ratios correspond to increased concentrations of chlorides throughout the tested slabs (*3*).

Tortuosity, as used in this research, is a measure of the twisted or winding nature of the path in which chloride ions can travel. Because ions travel through pore water in concrete, tortuosity is closely related to moisture content. As the moisture content increases, a greater interconnectivity, or continuity, of the pore water generally results in a more rapid progression of chlorides down through the concrete toward the level of the reinforcing steel. Higher degrees of water saturation therefore also correspond to higher diffusion coefficients (*14*). As the tortuosity, or complexity, of the concrete pore water structure remains unaltered, the diffusion coefficient can be considered to be constant (*13*).

The degree to which the concrete has hydrated will also affect the diffusion of chlorides into concrete bridge decks because, during hydration, the continuity of the pore structure is interrupted by the formation of calcium-silicate-hydrate (C-S-H), causing the pathway for chloride ions to become more tortuous (*14*). Again, higher tortuosity is associated with reduced diffusion coefficients.

Finally, exposure conditions, such as surface chloride concentrations and temperature, largely affect the amount of chlorides that can penetrate into the concrete substrate (*3*). Winter road maintenance practices directly affect the concentration of chlorides at the bridge deck surface. Bridge decks that receive more deicing salt applications will have greater chloride concentrations at the surface than those that receive lighter applications, all other factors held constant. In addition, higher temperatures are associated with higher diffusion rates and diffusion coefficients due to greater ionic mobility (*15, 16*). In this research, exposure conditions were directly or indirectly considered in the modeling process.

Over time, the accumulation of chlorides in concrete causes a breakdown of the naturally occurring protective environment that concrete provides for reinforcing steel. The otherwise passive oxide layer on the surface of the steel becomes unstable at elevated chloride concentrations and therefore becomes susceptible to corrosion. The higher the diffusion coefficient of the concrete, the quicker this transformation can occur.

2.3 STAY-IN-PLACE METAL FORMS

In this specific research, two types of concrete bridge decks were considered: decks with SIPMFs and decks without SIPMFs. Figure 2.1 shows the underside of a bridge deck constructed with SIPMFs.

Advantages associated with construction of bridge decks with SIPMFs include reduced labor costs, reduced construction time, and increased safety of construction workers (*12*). The forms are simple to construct on site, as they are lightweight and usually prefabricated. The SIPMFs can be quickly installed and, unlike conventional forms, are not removed after placement of the concrete. SIPMFs reduce safety hazards for bridge contractors, as bridge construction usually occurs over dangerous places such as ravines and highways (*12*).

Although decks with SIPMFs have numerous advantages over those without SIPMFs, they also have a higher potential for corrosion of reinforcing steel than decks without SIPMFs, primarily due to the fact that decks with SIPMFs have higher average moisture contents than decks without SIPMFs (*6*). Higher moisture contents facilitate

FIGURE 2.1 Bottom view of SIPMF.

higher diffusion coefficients and therefore result in greater ionic conduction (*6*). The higher moisture contents are a consequence of the reduction in evaporation of water from the bridge deck due to the presence of the SIPMFs along the bottom of the deck. Previous researchers determined that decks with SIPMFs exhibited diffusion coefficients approximately twice as high as those associated with decks without SIPMFs (*9*). In other words, the chloride ions were able to diffuse through the decks with SIPMFs almost twice as fast as through decks without SIPMFs. Because different diffusion coefficients would result in different rates of chloride accumulation, different rehabilitation practices would be expected for the different bridge deck types. Therefore, in the current project, decks with SIPMFs and decks without SIPMFs were both modeled to investigate the efficacy of SO procedures.

2.4 SCARIFICATION AND OVERLAYS

Although more costly than traditional surface treatments, concrete overlays are a common form of rehabilitation performed by DOTs when the concrete bridge deck has deteriorated to a condition of serious cracking and delamination, affecting the integrity of the bridge structure. Deteriorated concrete is first removed from the upper surface of the bridge deck through a scarification process. Scarification depths are often specified by bridge engineers based on the condition of the deck. These depths can range from 0.25 in. to below the top mat of reinforcing steel. Concrete removal is performed by heavy milling equipment, hydrodemolition equipment, jackhammers, or a combination of methods (*7*). Figure 2.2 shows a milling machine being used in this case to remove asphalt, while Figure 2.3 shows the removal of concrete by hydrodemolition. Figure 2.4 shows the process of jackhammering.

The process of removing the deteriorated concrete and preparing the surface can be tedious and must be performed carefully to avoid bruising and to provide a good bond between the existing concrete and the overlay being placed. Bruising is the formation of microcracks in concrete immediately below the interface of the existing concrete and the overlay (*19*). Weak bond strengths between the existing concrete and a newly placed overlay can be associated with bruising. In one document, researchers noted, “Tools that impact directly upon the concrete will create more damage than methods that impel a medium, such as a small abrasive, small steel shot, or high pressure water" (*19*, p. 45). Also, researchers involved in a study conducted in Virginia concluded, "Milling likely

FIGURE 2.2 Removal of asphalt by milling machine (*17*).

FIGURE 2.3 Removal of concrete by hydrodemolition (*18*).

FIGURE 2.4 Removal of concrete by jackhammering.

damages the old concrete surface" (*10*, p.10); the use of milling machines was attributed to the poor tensile bond strengths in the high performance concrete (HPC) overlays tested in that study. Poor bonding can lead to a shorter service life of the overlay by causing cracking and spalling. The overall objective of the scarification process is to remove deteriorated concrete while providing a rough but stable surface to which the new overlay can adequately bond. Figure 2.5 shows a deck prepared with a rough surface for a new overlay.

Overlays are typically designed to exceed the performance of the pre-existing concrete and are generally categorized as HPC. HPC is the term given to concrete that meets special requirements based on strength and/or durability (*20*). According to the American Concrete Institute, the enhanced properties of HPC are achieved using different constituents and construction techniques than used for normal concrete (*20*). The mix design for an HPC varies due to geographic location and project circumstances but commonly includes silica fume or latex modifiers for bridge deck overlay

FIGURE 2.5 Rough surface for bonding of new overlay.

applications (*21*). The addition of silica fume to the concrete mix decreases the capillary porosity and diffusivity of chloride ions due to the production of C-S-H and decreased interconnectivity of pores in the concrete (*22*). Latex, in a similar fashion, collects in the capillary pores during the hydration process, creating more dense and impermeable concrete (*23*). With respect to this research, HPC is therefore a concrete that has a high density and a low permeability. Although the technology associated with HPC has been available in the industry for more than half a century, the increasing demand for construction solutions on highway and commercial structures has resulted in more widespread use of HPC in recent years (*24*).

The time necessary to perform an SO treatment varies with the deck condition and type of overlay used. However, one researcher noted that for SO treatments using silica fume concrete composed of Type I/II cement, the process can be completed within 24 hours, ideally during a weekend to minimize disruption to traffic (*21*). The cost of an overlay using very-early-strength latex-modified concrete and conventional latex-modified concrete or silica fume concrete overlay is reported by one author to be $96 and $130 per square yard, respectively (*21*).

According to the literature review conducted in this research, HPC outperforms normal concrete when considering resistance to chloride-induced corrosion (*25, 26, 27*). Using HPC as an overlay can result in much lower diffusion coefficients and can therefore enhance the protection of reinforcing steel against the ingress of chlorides on bridge decks. Previous research conducted in Virginia involved the evaluation of a silica fume concrete overlay. The overlay was placed in 1994, and permeability tests were performed on samples cored from the deck at an age of 8 to 16 days and tested at 6 weeks. Permeability to chloride ions measured in coulombs was measured and recorded. The test results showed that the overlays were in a range of low to very low permeability. Five years later in 1999, more permeability tests were performed on cored samples from the deck. At that time, the permeability of the silica fume concrete was in the same low range as it had been at 6 weeks (*10*). While the previous research validates the effectiveness of HPC as a barrier against the intrusion of chlorides into the subsurface of the concrete, the timing at which application of treatment would protect the underlying reinforcing steel from reaching threshold levels of chloride concentrations during the service life of the deck was not considered in any of the articles identified in the literature review conducted for this research.

2.5 SUMMARY

Diffusion of chlorides is the primary mechanism by which damage occurs in concrete bridge decks in areas where deicing salts are applied. The water-to-cementitious materials ratio of the concrete mix, tortuosity and degree of saturation of the pore structure, degree of hydration of the concrete, and external environmental factors all contribute to the rate of diffusion of chlorides into concrete. High diffusion rates can lead to accelerated corrosion of reinforcing steel because chloride ions can more easily penetrate the concrete and create a corrosive environment. In particular, the presence of SIPMFs has been shown to increase diffusion rates due to the higher average water contents of decks equipped with these forms. Decks in these situations may therefore require earlier maintenance and rehabilitation procedures than those with lower diffusion rates. SO procedures are a common form of rehabilitation and must be performed with care to ensure an effective bond between the existing concrete and the new overlay. Using HPC in SO procedures can enhance the barrier between the external chlorides and the reinforcing steel, thus extending the service life of treated concrete bridge decks.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 OVERVIEW

The objectives of this research were met by conducting a questionnaire survey of state DOTs and performing numerical modeling of SO treatments. This chapter describes the methodology utilized in the DOT survey and presents the process followed and variables considered for numerical modeling.

3.2 QUESTIONNAIRE SURVEY

A questionnaire survey was conducted for the purpose of assessing the state of the practice concerning SO procedures applied to concrete bridge decks throughout the United States and to facilitate numerical modeling of typical approaches. The DOTs were chosen based on the climate of the geographic region and previous knowledge of SO treatment usage by DOT personnel. The climates of the selected states were those with winter seasons harsh enough for winter road maintenance in the form of deicing salts or chemicals. A total of 44 DOTs were contacted, and personnel in the following 40 states responded: Alaska, Arizona, Arkansas, California, Colorado, Connecticut, Delaware, Idaho, Illinois, Indiana, Iowa, Kansas, Kentucky, Maryland, Massachusetts, Michigan, Minnesota, Missouri, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, North Dakota, Ohio, Oklahoma, Oregon, Rhode Island, South Dakota, Tennessee, Texas, Utah, Vermont, Virginia, Washington, West Virginia, and Wyoming. The survey was conducted by telephone and e-mail. Participants in the survey were typically state bridge engineers or state bridge maintenance engineers. Each DOT participant was asked the following questions regarding rehabilitation procedures on concrete bridge decks:

- What is a typical range for scarification depth?
- What is a typical range for overlay thickness?
- What types of overlays are used in your specific state (HPC, low slump, etc.)?

Based on the answers to these questions, appropriate ranges of SO depth were selected for use in the modeling process. The use of typical values ensured that the numerical modeling would have maximum utility for practitioners working in the area of bridge management.

3.3 NUMERICAL MODELING

Chloride penetration profiles were obtained using a numerical modeling program developed by the National Institute of Standards and Technology (*28*). The program uses the one-dimensional approximation for diffusion based on Fick's second law to simulate the diffusion of chlorides through concrete. The program considers several internal and external variables that contribute to the intrusion of chlorides into concrete. The internal variables that are considered in the program are the concrete mix design parameters such as water-cementitious materials ratio, air content, degree of hydration, and diffusion coefficient. Specific diffusion coefficients were used for decks with and without SIPMFs. The external variables for which the program accounts are average monthly temperature, surface chloride concentration, and unexposed boundary condition for the concrete. The unexposed boundary condition may be simulated as a "reflecting boundary" or "constant at zero" as stated in the software; these options account for the presence of decks with and without SIPMFs, respectively (*28*). Accounting for all of these variables together allows for extensive approximations of chloride concentration profiles based on the cyclic loading of chlorides on bridge decks.

The function used to represent the chloride concentration at the surface 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

This function was developed by previous BYU researchers (*9*). In the process of its development, concrete samples were collected on Utah bridge decks and subjected to chloride extraction in the BYU Highway Materials Laboratory to determine the chloride concentration profiles for a total of 12 decks, six with and six without SIPMFs. Pulverized concrete samples were extracted at 1-in. depth increments throughout the deck profile at six randomly selected locations on each deck. After the chloride profiles were established, an iterative process was used to determine the function representing the external concentration of chlorides through time that provided the best match between the modeled and measured concentration profiles for decks with and without SIPMFs. In this iterative process, both the chloride surface concentration and the diffusion coefficients of each investigated profile were simultaneously altered to produce a single chloride surface concentration model that provided the best possible matches between simulated and measured chloride data.

Specific inputs for the program were determined from local climatic conditions and with assistance from personnel at the National Institute of Standards and Technology and the Federal Highway Administration High Performance Concrete Technology Implementation Panel (*29*). The diffusion coefficients for decks with and without SIPMFs were determined in the previous BYU research through an iterative process followed for each of the 12 decks. Diffusion coefficients determined for each tested profile were those associated with minimum sums of squared differences between the modeled chloride profiles and the actual measured concentrations (*9*). After this process was complete, the average diffusion coefficients were calculated to be 2.72E-11 m^2/s and 1.30E-11 m^2/s for decks with and without SIPMFs, respectively. These values were also adopted for the current study.

For SO treatments investigated in this research, the diffusion coefficient assigned to the HPC overlay was 1.00E-12 m^2/s. The diffusion of chlorides in HPC overlays is 27 times slower than in decks with SIPMFs and 13 times slower than in decks without SIPMFs. Table 3.1 contains the specific and default values used in the modeling performed in this research. The “Typical” column in the table refers to the original concrete that exists on the simulated deck prior to rehabilitation, while the “Overlay” column refers to the overlay placed on the deck following scarification. Table 3.2 displays the monthly temperature inputs used in the modeling process. Both tables are presented in metric units as required in the program.

The various treatments modeled were selected based on the responses received in the questionnaire survey conducted in this study. Specific scarification depths chosen for numerical modeling were 0.5, 1.0, and 1.5 in., while overlay depths of 1.5 and 2.0 in. were chosen. The depths for SO were combined in a full-factorial experimental design to form all possible combinations, producing a total of six unique treatments. OCDs of 2.0, 2.5, and 3.0 in., as measured from the surface of the deck to the top layer of reinforcing steel, were used to simulate different bridge design practices (*7*), and

TABLE 3.1 Computer Program Input Values

Property	Value	
	Typical	Overlay
Beginning Month of Exposure	October	
Member Thickness (m)	0.203	
Water Cementitious Material ratio, w/cm	0.44	0.39
Degree of Hydration	0.8	
Volume Fraction of Aggregate (%)	65	62
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 of Binding (s^{-1})	1.00E-07	
C_3A Content of Cement (%)	5	
C_4AF Content of Cement (%)	5	
Rate Constant for Aluminate Reations with Chloride (s^{-1})	1.00E-08	

TABLE 3.2 Monthly Temperature Inputs

Month	Temperature (°C)
January	-2.3
February	1.2
March	5.4
April	9.8
May	14.9
June	20.6
July	25.5
August	24.2
September	18.4
October	11.8
November	4.9
December	-1.3

simulations involving decks with and without SIPMFs were also performed. In all, fully crossing all the levels of these various factors produced a total of 36 unique scenarios.

The numerical modeling for each scenario was carried out to a total simulated service life of 50 years. Modeling times were chosen to start at a simulated deck age of 2 years and advanced at 2-year increments through a service life of 20 years. Beginning at year 20, modeling was performed at 5-year increments through a service life of 50 years. First, modeling of the decks without treatment was performed. Second, the modeling process was performed for each combination of treatment and timing. The latest scheduled time of SO treatment that resulted in a chloride concentration, at the level of reinforcing steel, that most nearly approached the threshold level of chloride concentration of 2 lb of chloride per cubic yard of concrete without exceeding it during the 50 year service life was chosen as the latest recommended initial timing of the SO treatment. To limit the number of required simulations and to present the data clearly, the modeling was performed for three treatment times before and three treatment times after the threshold concentration of chlorides was reached. This approach facilitated determination of the most effective initial timing of SO treatment and analysis of the chloride concentrations in the decks associated with premature and delayed treatment.

As an aid in understanding the process of the numerical modeling, an example is presented. An 8-in.-thick deck with an SIPMF and an OCD of 3.0 in. was constructed and completed in the month of October. The scarification and overlay depths specified for this simulation were 1.0 in. and 2.0 in., respectively. Thus, the desired result of the numerical modeling in this case is identification of the latest year that a 1.0-in. scarification may be performed and a 2.0-in. overlay placed without allowing the top mat of reinforcing steel to experience a chloride concentration of 2 lb of chloride per cubic yard of concrete, or greater, during the deck lifetime of 50 years. As the researcher does not know in advance the exact treatment timing that will prove successful, a guess of 2 years is chosen as a time of treatment in this example. All program inputs described previously are entered along with the specified time of SO treatment as day 730, which corresponds to 2 years, under the options in the program for the SO treatment. In the program, the input "Beginning Month of Exposure" is also the month in which the SO treatment will be performed if yearly increments are utilized. Also, the SO procedure is accounted for one day immediately following the day specified as the time of treatment. In this example, the SO treatment will therefore be applied exactly two years from the day of construction in the month of October. The researcher then runs the model, involving an SO treatment at 2 years, for each of the following deck service lives: 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 25, 30, 35, 40, 45, and 50 years. The output for each simulation is a chloride profile of the deck showing the vertical distribution of chlorides at that time. An important consideration is the net change in overall deck thickness once this particular 1.0-in. scarification and 2.0-in. overlay is performed. The net change in thickness in this case is 1.0 in., meaning that the bridge deck is now a total of 9.0 in. thick. In addition, the net cover depth has increased by 1.0 in., meaning that the top mat of reinforcement is now located 4.0 in. below the surface of the deck. The implications of this net increase in concrete cover are explained in more detail in Chapter 4.

After each set of simulations is complete, the researcher evaluates the chloride concentrations at the level of the rebar over the full 50 years and determines if the critical chloride concentration was exceeded. If so, an earlier SO treatment time is evaluated in the next set of simulations; if not, a later SO treatment time is evaluated. This approach was followed for simulating all of the SO treatments of interest until the maximum SO delay time, in 2-year increments, was identified for each scenario, after which at least three consecutive treatment times before and three consecutive treatment times after the specified year were simulated. Two-year increments were used until year 20 was reached or until the final treatment time was evaluated, whichever corresponded to the greatest deck age, after which 5-year increments were utilized.

3.4 SUMMARY

In accordance with the objectives of this research, a questionnaire survey of state DOTs was conducted, and numerical modeling of SO treatments was performed. Data collected from the survey of DOT personnel and data from the literature were considered in selection of OCDs, scarification depths, and overlay thicknesses for modeling in this work. A formula for surface chloride concentrations developed by previous researchers and average monthly temperatures were used as inputs in the modeling process. In addition, simulations involving both decks with and without SIPMFs were performed. Numerical modeling was then performed for each unique combination of variables through a service life of 50 years to determine the recommended initial timing of SO treatment in each case.

CHAPTER 4
RESULTS

4.1 OVERVIEW

The results of the questionnaire survey and numerical modeling are presented in the following sections. A brief discussion of these results in light of previous research findings is also provided.

4.2 QUESTIONNAIRE SURVEY

The results of the survey indicate a lack of uniformity among DOT specifications, as a variety of rehabilitation procedures were described by the individual survey participants. Of the 40 DOTs that responded to the survey, 20 use a scarification depth between 0.5 in. and 1.5 in., and 27 use an overlay depth between 1.5 in. and 2.0 in. All of the DOTs reported using HPC that resulted in a lower permeability and/or higher density, meaning that the diffusion rate is significantly lower than normal concrete. The most common types of HPC used are micro-silica fume (SF) and latex-modified concrete (LMC). Table 4.1 presents the typical scarification and overlay depths reported by each responding state DOT, along with the type of HPC used. The Connecticut, Massachusetts, and New Hampshire DOT respondents stated that they place hot mix asphalt on their decks and do not perform concrete overlays. The Rhode Island DOT participant reported that SO procedures are rare and that deck replacements are typically specified instead. The New Mexico DOT engineer provided the same response, citing a low benefit-cost ratio associated with overlays in that state.

Table 4.1 Results of Questionnaire Survey

State	Typical Range for Scarification Depth (in.)	Typical Range for Overlay Depth (in.)	Type of HPC Overlay
Alaska	3.5 - 4.0	3.5 - 4.0	SF
Arizona	1.5 - 2.0	1.5 - 2.0	SF, Polymer Epoxy
Arkansas	0.5	0.5	LMC
California	1.0 - 1.5	0.75 - 3.0	Polyester
Colorado	0.25	0.375 - 2.0	SF
Delaware	1.5	1.5	SF, LMC
Idaho	1.5	1.5	SF
Illinois	0.25 - 0.375	0.375 - 2.5	SF, LMC, Polymer
Indiana	0.25	1.75	LMC
Iowa	0.25	1.75	High Density/Low Slump
Kansas	2.0 - 3.0	1.5	SF
Kentucky	2.5	2.5	LMC
Maryland	2.0	2.0	LMC
Michigan	1.5 - 2.0	2.75	SF, LMC
Minnesota	0.25 - 1.5	2.0	Low Slump
Missouri	0.25	0.25 - 2.25	SF, LMC, Epoxy Polymer
Montana	0.75	1.5 - 2.0	LMC
Nebraska	0.5	2.0	SF
Nevada	0.25	0.75	Polyester, Epoxy
New Jersey	1.5	1.5	SF, LMC
New York	0.25 - 0.5	2.0	SF
North Carolina	0.5 - 1.5	0.5 - 1.5	LMC, High Early Strength
North Dakota	0.5	1.5	Portland Cement Concrete
Ohio	1.0 - 1.5	1.5 - 2.0	LMC
Oklahoma	0.375	1.5	High Early Strength
Oregon	0.25	1.5	SF
South Dakota	0.25	2.0	Low Slump
Tennessee	1.0	1.25	LMC
Texas	1.0	1.5 - 2.0	LMC
Utah	1.0 - 1.5	1.25 - 3.0	SF
Vermont	3.5	3.5	Portland Cement Concrete
Virginia	1.25	1.5	LMC
Washington	0.5	1.5	SF, LMC, Fly Ash
West Virginia	1.5	1.5	LMC
Wyoming	0.25	1.25	SF

4.3 NUMERICAL MODELING

In Appendices A and B, graphs of chloride concentrations at the level of the reinforcing steel over time for OCDs of 2.0 in., 2.5 in., and 3.0 in. are presented for decks with and without SIPMFs, respectively. In these graphs, three treatment times are shown before and after the threshold level of chlorides was reached at the level of reinforcing steel in each case. These allow for the latest effective initial timing of SO treatment to be determined and for the effects of premature and delayed treatment on chloride concentrations to be analyzed. Appendices C and D present graphs displaying chloride concentration profiles of the simulated decks with and without SIPMFs, respectively, for the years of recommended treatment. Preparation of these graphs required completion of approximately 1300 simulations. Chloride concentration profiles beyond those corresponding to the recommended treatment times are not included due to the excessive numbers of graphs that would be required.

Tables 4.2 to 4.7 present the recommended latest timing for initial SO procedures for the different deck types for the values of OCD, scarification, and overlay depths simulated. Tables 4.2 to 4.4 present data for decks with SIPMFs, while Tables 4.5 to 4.7 present data for decks without SIPMFs.

As an aid in understanding the process of data organization and reduction, an example is presented. In Figure C.16, chloride concentration profiles for an 8-in.-thick deck with an SIPMF and an OCD of 3.0 in. are presented for a scenario in which an SO treatment was applied at year 6 of the deck life in the month of October. The scarification and overlay depths specified for this simulation were 1.0 in. and 2.0 in., respectively. Each series of points, which were obtained directly from the software program utilized in this research, represents a specific year ranging from year 2 through year 50. In the process of data analysis, the chloride concentration at the depth of the reinforcing steel, 3.0 in., was determined from the graph through year 6 and recorded in a spreadsheet. At year 6, the SO treatment was simulated and is taken into account in the data produced for the next simulated year, which is year 8. At this year, the chloride concentration was determined from the graph at a depth of 4 in. for recording in the same spreadsheet. Although the position of the steel did not change, its depth relative to the surface of the concrete increased in this example due to the fact that the 1.0-in.

scarification and subsequent 2.0-in. overlay resulted in an increase in cover thickness of 1.0 in.

From year 8 to year 50, the chloride concentrations were then determined from the graph at the 4.0-in depth and recorded similarly. All of these recorded concentrations were then plotted in Figure A.16 under the series named "Treatment at 6 years," and this process was repeated for every other treatment timing displayed in the figure. Then, again with reference to Figure A.16, the series with the maximum chloride concentration over the 50-year service life that was most nearly equal to but not exceeding 2 lb of chloride per cubic yard of concrete was identified as the latest recommended timing for initial SO procedures; in this example, the "Treatment at 6 years" series was selected. Year 6 was then entered in Table 4.3 in the correct row and column. This process was continued for each SO treatment combination and OCD. The process was the same for decks without SIPMFs, but those data are contained in Appendices B and D as mentioned previously.

Overall, the bridge decks without SIPMFs could endure delays in SO treatments for a greater amount of time than those with SIPMFs. For example, with an OCD of 3.0

TABLE 4.2 Recommended Latest Timing of SO Procedure for Deck with SIPMF and with 2.0-in. OCD

2.0-in. Original Cover Depth	Scarification Depth (in.)		
	0.5	1.0	1.5
Overlay Depth (in.)	Recommended Deck Age for Treatment (yr)		
1.5	2	2	2
2.0	2	2	2

TABLE 4.3 Recommended Latest Timing of SO Procedure for Deck with SIPMF and with 2.5-in. OCD

2.5-in. Original Cover Depth	Scarification Depth (in.)		
	0.5	1.0	1.5
Overlay Depth (in.)	Recommended Deck Age for Treatment (yr)		
1.5	2	4	4
2.0	2	4	4

TABLE 4.4 Recommended Latest Timing of SO Procedure for Deck with SIPMF and with 3.0-in. OCD

3.0-in. Original Cover Depth	Scarification Depth (in.)		
	0.5	1.0	1.5
Overlay Depth (in.)	Recommended Deck Age for Treatment (yr)		
1.5	4	6	6
2.0	4	6	6

TABLE 4.5 Recommended Latest Timing of SO Procedure for Deck without SIPMF and with 2.0-in. OCD

2.0-in. Original Cover Depth	Scarification Depth (in.)		
	0.5	1.0	1.5
Overlay Depth (in.)	Recommended Deck Age for Treatment (yr)		
1.5	6	6	6
2.0	6	6	6

TABLE 4.6 Recommended Latest Timing of SO Procedure for Deck without SIPMF and with 2.5-in. OCD

2.5-in. Original Cover Depth	Scarification Depth (in.)		
	0.5	1.0	1.5
Overlay Depth (in.)	Recommended Deck Age for Treatment (yr)		
1.5	10	10	10
2.0	10	10	10

TABLE 4.7 Recommended Latest Timing of SO Procedure for Deck without SIPMF and with 3.0-in. OCD

3.0-in. Original Cover Depth	Scarification Depth (in.)		
	0.5	1.0	1.5
Overlay Depth (in.)	Recommended Deck Age for Treatment (yr)		
1.5	16	18	18
2.0	16	18	18

in., a scarification depth of 1.5 in., and an overlay thickness of 2.0 in., the deck with SIPMFs did not experience critical chloride concentrations at the level of the reinforcing steel until 6 years of service life, while the deck without SIPMFs did not experience critical chloride concentrations until 18 years of service life. In all cases, the absence of SIPMFs extended the amount of time before an SO treatment was needed.

The results of this research indicate that, on average, the additional period of delay allowed before an SO treatment was required in decks with SIPMFs was 2 years with each additional 0.5 in. of OCD. In decks without SIPMFs, the presence of a greater OCD had a more pronounced effect on the latest recommended timing of treatment than in the decks with SIPMFs; an average additional delay period of 5 years was obtained with each additional 0.5 in. of OCD in decks without SIPMFs.

At the times recommended for most of the SO treatments, the chloride concentrations at the level of the reinforcing steel were not at the threshold value of 2 lb of chloride per cubic yard of concrete. Though maintenance procedures may initially seem premature at this stage, the SO treatment must take place. The chlorides not removed by the SO treatment may be sufficient to cause corrosion-inducing levels of chloride concentrations at the level of reinforcing steel in the future, due to downward diffusion, even if no additional chlorides enter the deck.

As an illustration of this point, Figure 4.1 shows the chloride concentration profile for a deck without SIPMFs and an OCD of 3.0 in. at year 18 just before the application of an SO treatment involving scarification and overlay depths of 0.5 in. and 2.0 in., respectively. The chloride concentration at the level of the reinforcing steel is noted in the figure as being 1.9 lb of chloride per cubic yard of concrete, which is below the threshold at which corrosion would be expected to begin. However, after application of the SO treatment at year 18, the chloride concentration at the level of the reinforcing steel, now at a depth of 4.5 in. as shown in Figure 4.2, increased to 2.3 lb of chloride per cubic yard of concrete by year 20. The reason that the threshold was exceeded is that the chlorides in the pre-existing concrete, not removed by the SO treatment, continued to diffuse through the concrete and resulted in elevated chloride concentrations at the level of reinforcing steel.

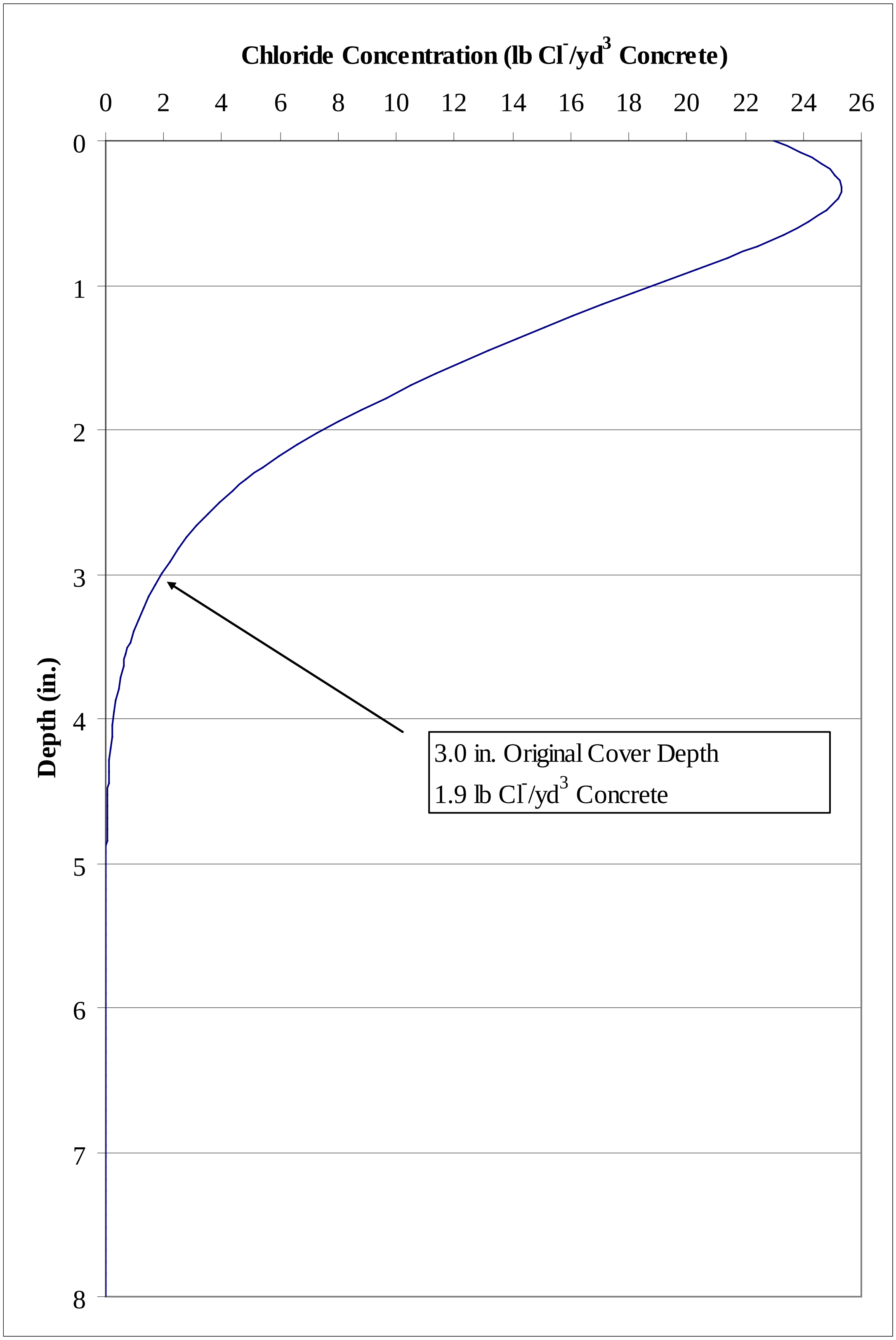

FIGURE 4.1 Scenario of deck with SIPMFs at year 18 (before treatment).

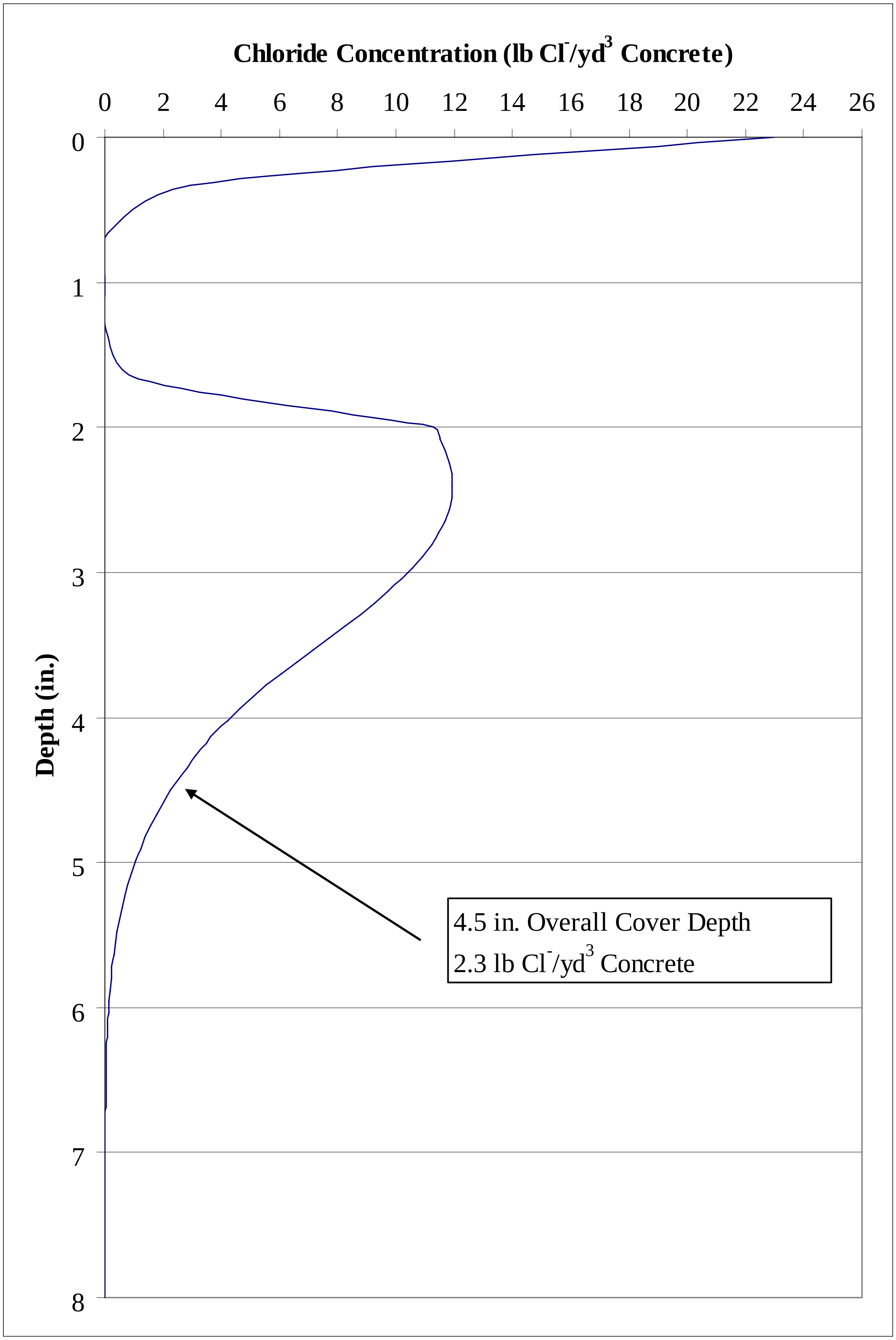

FIGURE 4.2 Scenario of deck with SIPMFs at year 20 (after treatment).

A correct timing of the SO treatment ensures that chloride concentrations at the level of the reinforcing steel always remain below 2.0 lb of chloride per cubic yard of concrete. In the scenario just described, application of an SO treatment at 16 years is appropriate for this reason. Figure 4.3 shows the chloride concentration profile for the same deck at year 16 just before the SO treatment, at which time the chloride concentration at the level of the reinforcing steel is just 1.5 lb of chloride per cubic yard of concrete. In this case, although the chloride concentration does increase by year 18 to 1.9 lb of chloride per cubic yard of concrete as shown in Figure 4.4, the value is still below the threshold.

Although applying the SO treatment at 16 years in this latter example does in fact adequately minimize the chloride concentration at the level of the reinforcing steel through the entire 50 years of simulated deck life, this example of good practice did not explicitly include examination of years beyond 18; the chloride concentrations at the level of the reinforcing steel for all years remaining in the defined service life of the deck should always be investigated in this process of determining the latest allowable timing of an SO treatment. In this research, all simulations were continued to a deck life of 50 years, at which time most of the decks, including those treated at the recommended times and those for which the SO treatments were delayed, had concentrations of chlorides at the reinforcing steel well below the threshold of 2 lb of chloride per cubic yard of concrete; thus, in these scenarios, the SO treatment was performed before chlorides accumulated to such a degree that their equilibration throughout the profile after HPC placement might have resulted in chloride concentrations above the established threshold.

Scarification depth played a greater role than overlay depth when reductions in chloride concentration at the level of reinforcing steel were considered. Due to the low diffusion rate of the HPC overlay, the two different overlay depths of 1.5 in. and 2.0 in. were not distinguishable; they both provided sufficient obstruction against intrusion of chlorides into the subsurface of the concrete during the simulated service life of 50 years. These findings demonstrate that HPC is an effective barrier against the ingress of chlorides in concrete bridge decks.

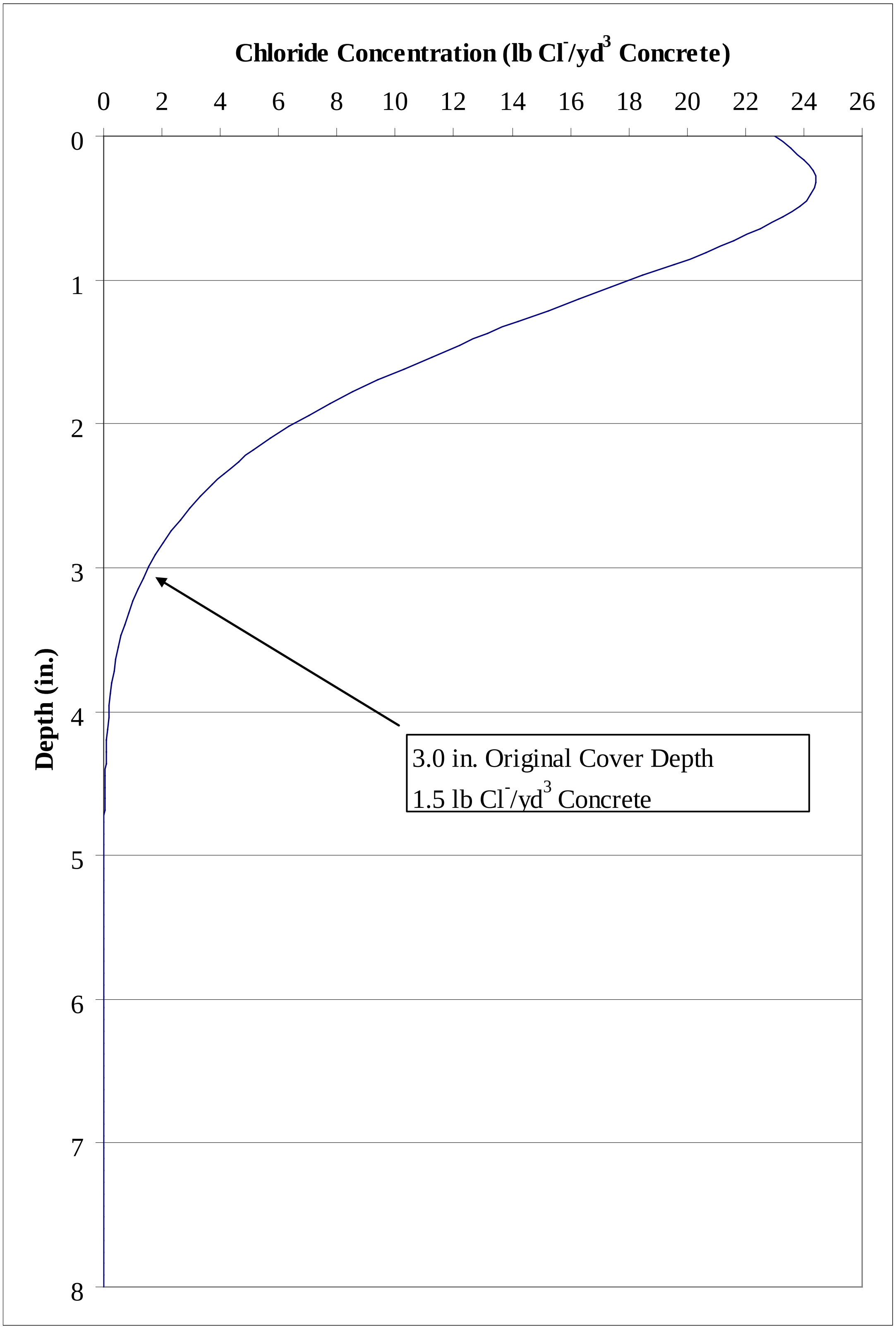

FIGURE 4.3 Scenario of deck with SIPMFs at year 16 (before treatment).

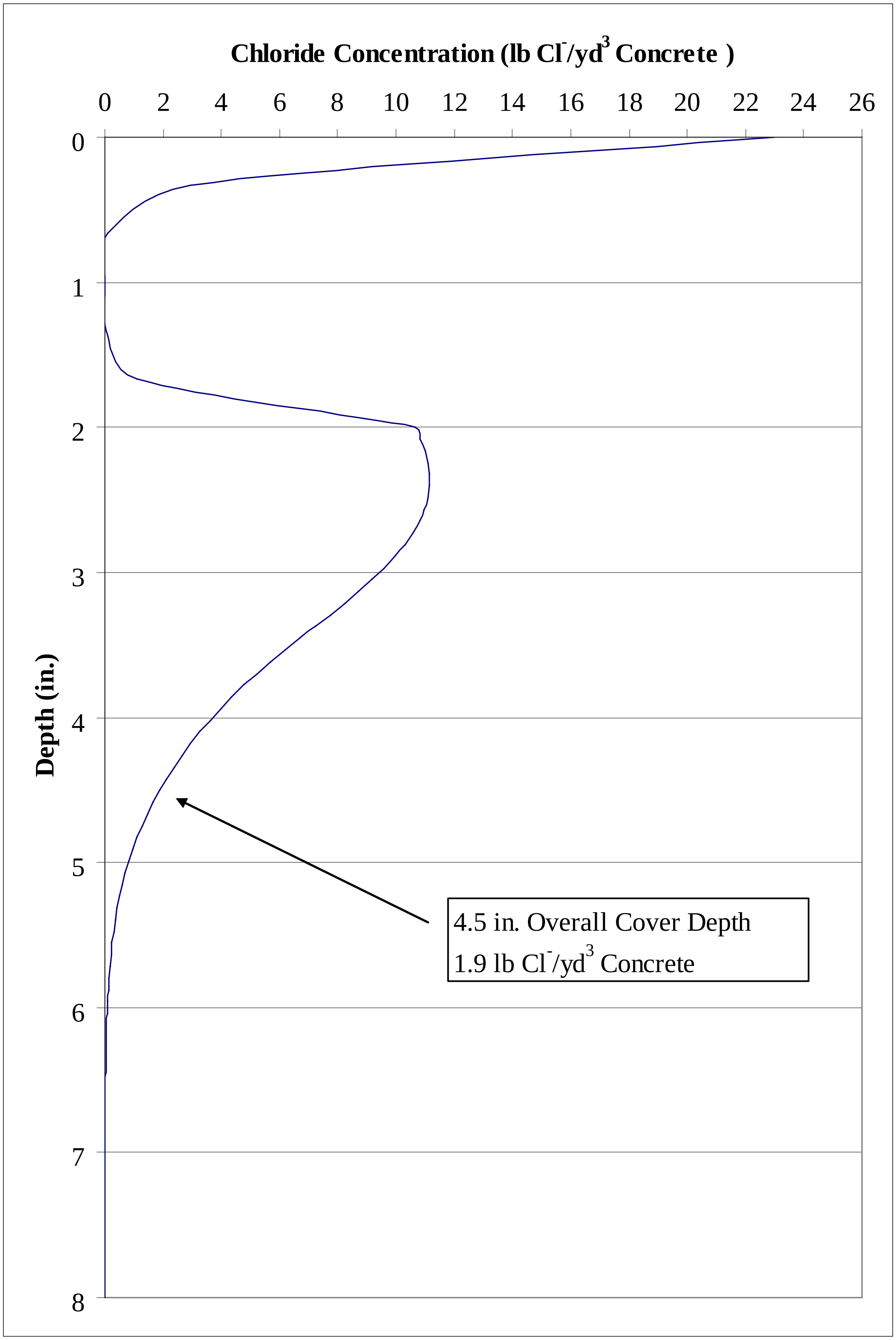

FIGURE 4.4 Scenario of deck with SIPMFs at year 18 (after treatment).

The SO treatment proposed in this research is only for the initial application of the treatment. As overlays are not permanent, repeated treatments may be necessary in practice to ensure that critical concentrations of chlorides do not accumulate in the concrete deck.

4.4 MAINTENANCE AND REHABILITATION COMPARISON

To facilitate a constructive comparison between use of surface treatments for maintenance and SO treatments for rehabilitation of concrete bridge decks, the recommended latest timing for surface treatments, resulting from previous BYU research, is replicated in Table 4.8 (*30*).

From the current research, the least extensive treatment of 0.5-in. scarification and 1.5-in. overlay yielded the results presented in Table 4.9. Table 4.10 contains the results of the most extensive treatment of 1.5-in. scarification and 2.0-in. overlay.

The recommended latest timing of surface treatment application for an OCD of 2.0 in. was at years 1 and 5 for decks with and without SIPMFs, respectively. For the least extensive SO treatment of a 0.5-in. scarification and a 1.5-in.overlay, the recommended timing was at years 2 and 6 for decks with and without SIPMFs,

TABLE 4.8 Recommended Latest Timing of Surface Treatment Application

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

TABLE 4.9 Recommended Latest Timing of 0.5-in. Scarification and 1.5-in. Overlay Treatment

Cover Depth (in.)	Deck Age for Scarification and Overlay Treament (yr)	
	With SIPMFs	Without SIPMFs
2.0	2	6
2.5	2	10
3.0	4	16

TABLE 4.10 Recommended Latest Timing of 1.5-in. Scarification and 2.0-in. Overlay Treatment

Cover Depth (in.)	Deck Age for Scarification and Overlay Treament (yr)	
	With SIPMFs	Without SIPMFs
2.0	2	6
2.5	4	10
3.0	6	18

respectively. For the most extensive SO treatment of a 1.5-in. scarification and a 2.0-in. overlay, the recommended timing was at years 2 and 6 for decks with and without SIPMFs, respectively. In essence, the model showed that one additional year of delay was obtained from performing an SO treatment, whether more or less aggressive, in comparison to a surface treatment.

For an OCD of 2.5-in., the recommended latest timing of surface treatment application was at years 3 and 9 for decks with and without SIPMFs, respectively. The recommended timing for the least extensive SO treatment was at years 2 and 10 for decks with and without SIPMFs, respectively, while the recommended timing for the most extensive SO treatment was at years 4 and 10 for decks with and without SIPMFs, respectively. The modeling showed that, for a deck with SIPMFs, a surface treatment was required at year 3, while the least extensive SO treatment was required at year 2; in theory, an SO treatment should not be required before a surface treatment. The discrepancy in these results can be explained by the increments used in the modeling. During the modeling of the surface treatment, 1-year iterations were utilized. However, to reduce the number of iterations in the modeling process for SO treatments, which involved more variables, 2-year increments were utilized. Use of the 2-year increment resulted in the apparent need for an SO treatment a year earlier than the surface treatment at a 2.5-in. OCD. In all other cases, treatment could be delayed an additional year when performing an SO treatment compared to a surface treatment.

For an OCD of 3.0 in., the recommended latest timing of surface treatment application was at years 5 and 15 for decks with and without SIPMFs, respectively. The recommended timing for the least extensive SO treatment was at years 4 and 16 for decks with and without SIPMFs, respectively, while the recommended timing for the most extensive SO treatment was at years 6 and 18 for decks with and without SIPMFs, respectively. The same discrepancy, as mentioned in the previous paragraph, occurred between the surface treatment and least extensive SO treatment in the decks with SIPMFs for the same reason given earlier. For decks without SIPMFs, treatment could be delayed an additional year when performing the least extensive SO treatment and an additional 3 years when performing an extensive SO treatment when compared with a surface treatment.

Given that a report published in 2001 estimated the total cost of an epoxy overlay, a common form of surface treatment, at $32 per square yard and the total cost of a conventional latex-modified concrete or silica fume concrete overlay at $130 per square yard (*21*), the latter is obviously much more expensive. Given the amount of time and money that is needed to perform an SO treatment, the additional delay time of one to three years through the SO process is not worth the associated cost. Instead, for decks similar to those investigated in this study, the best method to follow is to apply a surface treatment before the latest timing recommended in previous research at BYU. If the bridge deck is beyond the point of effective surface treatment, an SO treatment may be considered next. However, the window of opportunity is narrow between the application of a surface treatment and an SO treatment. If the concrete bridge decks under consideration have material properties, climatic effects, and salt exposures similar to those simulated in this research, the latest recommended treatment timing proposed in this research should be followed. Decks with conditions beyond those appropriate for SO treatment may require complete replacement, which is by far the most expensive option, estimated at $800 per square yard in Utah (personal communication, D. Eixenberger, Utah DOT, October 2007).

4.5 SUMMARY

Chloride concentrations at OCDs of 2.0 in., 2.5 in., and 3.0 in. were determined from modeled profiles for all SO treatment depths. The resulting chloride concentrations were compiled to form graphs showing the effect of treatment timing on chloride concentration at the top mat of reinforcing steel. These figures were used to obtain the recommended latest timing of SO treatment by locating the treatment time resulting in a maximum chloride concentration at the level of reinforcing steel nearest but still below the threshold of 2 lb of chloride per cubic yard of concrete over the simulated 50-year deck service life.

The research results show that, overall, bridge decks without SIPMFs can endure longer delays in SO treatment timing than those with SIPMFs; in all cases, the absence of SIPMFs extended the amount of time before an SO treatment was needed. On average, the additional period of delay allowed before an SO treatment was required in decks with SIPMFs was 2 years with each additional 0.5 in. of OCD. In decks without SIPMFs, the presence of a greater OCD had a more pronounced effect on the latest recommended timing of treatment than in the decks with SIPMFs; an average additional delay period of 5 years was obtained with each additional 0.5 in. of OCD in decks without SIPMFs.

At the times recommended for most of the SO treatments, the chloride concentrations at the level of the reinforcing steel were not at the threshold value of 2 lb of chloride per cubic yard of concrete. Though maintenance procedures may initially seem premature at this stage, the SO treatment must take place. The chlorides not removed by the SO treatment may be sufficient to cause corrosion-inducing levels of chloride concentrations at the level of reinforcing steel in the future, due to downward diffusion, even if no additional chlorides enter the deck.

Scarification depth played a greater role than overlay depth when reductions in chloride concentration at the level of reinforcing steel were considered. Due to the low diffusion rate of the HPC overlay, the two different overlay depths of 1.5 in. and 2.0 in. were not distinguishable; they both provided sufficient obstruction against intrusion of chlorides into the subsurface of the concrete during the simulated service life of 50 years. These findings demonstrate that HPC is an effective barrier against the ingress of chlorides in concrete bridge decks.

For decks similar to those investigated in this study, the best method to follow is to apply a surface treatment before the latest timing recommended in previous research at BYU. If the bridge deck is beyond the point of effective surface treatment, an SO treatment may be considered next. However, the window of opportunity is narrow between the application of a surface treatment and an SO treatment. If the concrete bridge decks under consideration have material properties, climatic effects, and salt exposures similar to those simulated in this research, the latest recommended treatment timing proposed in this research should be followed. Decks with conditions beyond those appropriate for SO treatment may require complete replacement, which is by far the most expensive option.

CHAPTER 5
CONCLUSION

5.1 SUMMARY

Considering the pervasive presence of chlorides in concrete bridge decks, bridge engineers have a critical responsibility to perform proper and effective preventive maintenance and rehabilitation operations. Bridge engineers often perform SO procedures on concrete bridge decks to minimize the corrosion of reinforcing steel due to chloride ingress. Derived from the need to develop guidelines for the initial timing of SO treatments, the specific objectives of this research were to collect information from several DOT personnel about their SO procedures and, subsequently, to determine the recommended timing of initial SO procedures on concrete bridge decks for preventing the accumulation of corrosion-inducing levels of chlorides and extending deck service life.

In accordance with the objectives of this research, a questionnaire survey of state DOTs was conducted, and numerical modeling of SO treatments was performed. Data collected from the survey of DOT personnel and data from the literature were considered in selection of OCDs, scarification depths, and overlay thicknesses for modeling in this work. A formula for surface chloride concentrations developed by previous researchers and average monthly temperatures were used as inputs in the modeling process. In addition, simulations involving both decks with and without SIPMFs were performed. Numerical modeling was then performed for each unique combination of variables through a service life of 50 years to determine the recommended initial timing of SO treatment in each case.

5.2 FINDINGS

The research results show that, overall, bridge decks without SIPMFs can endure longer delays in SO treatment timing than those with SIPMFs; in all cases, the absence of SIPMFs extended the amount of time before an SO treatment was needed. For decks with SIPMFs, the allowable delay in SO timing ranged from 2 to 6 years, while on decks without SIPMFs the allowable delay in SO timing ranged from 6 to 18 years. These delays are only 1 to 3 years longer than allowable delays associated with placement of surface treatments investigated in previous research.

On average, the period of additional delay allowed before an SO treatment is required in decks with SIPMFs was 2 years with each additional 0.5 in. of OCD. In decks without SIPMFs, the presence of a greater OCD had a more pronounced effect on the latest recommended timing of treatment than in the decks with SIPMFs; an average additional delay period of 5 years was obtained with each additional 0.5 in. of OCD in decks without SIPMFs.

Scarification depth played a greater role than overlay depth when reductions in chloride concentration at the level of reinforcing steel were considered. Due to the low diffusion rate of the HPC overlay, the two different overlay depths of 1.5 in. and 2.0 in. were not distinguishable; they both provided sufficient obstruction against intrusion of chlorides into the subsurface of the concrete during the simulated service life of 50 years. These findings demonstrate that HPC is an effective barrier against the ingress of chlorides in concrete bridge decks.

5.3 RECOMMENDATIONS

For decks similar to those investigated in this study, the best method to follow is to apply a surface treatment before the latest timing recommended in previous research at BYU. If the bridge deck is beyond the point of effective surface treatment, an SO treatment may be considered next. However, the window of opportunity is narrow between the application of a surface treatment and an SO treatment. If the concrete bridge decks under consideration have material properties, climatic effects, and salt exposures similar to those simulated in this research, the latest recommended treatment timing proposed in this research should be followed. Decks with conditions beyond those appropriate for SO treatment may require complete replacement, which is by far the most expensive option.

Together with the findings of this research and the specific properties of the bridge deck under scrutiny, engineers can determine the appropriate timing of rehabilitation procedures to prevent or mitigate corrosion of the steel reinforcement of a bridge deck and ensure the usability of the deck for its intended service life. However, SO treatments should be considered only after determining that a surface treatment would prove to be unsuccessful. Although the conditions studied in this research were consistent with bridges located in the state of Utah, bridge decks that exist in similar environments and that are subjected to similar treatments of deicing salts as part of winter maintenance could exhibit similar properties to the decks simulated in this research. Engineers should carefully consider the results of this research and implement proper timing of SO treatments on their respective bridge decks to protect against and minimize the effects of corrosion due to chloride ingress.

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APPENDIX A:

CHLORIDE CONCENTRATIONS AT LEVEL OF REINFORCING STEEL FOR DECKS WITH STAY-IN-PLACE METAL FORMS

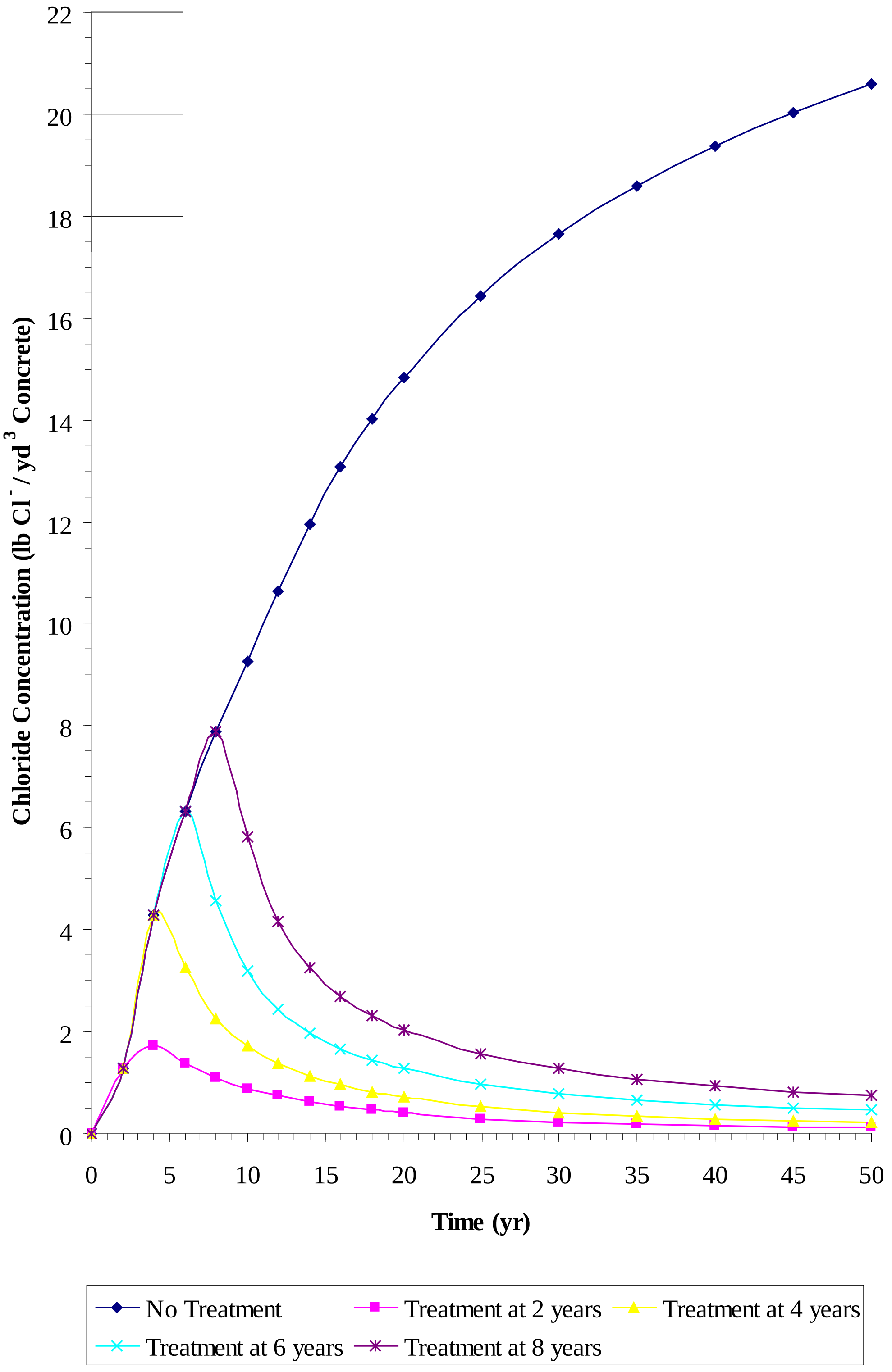

FIGURE A.1 Chloride concentrations of decks with SIPMFs with 2.0-in. OCD for 0.5-in. scarification and 1.5-in. overlay treatments.

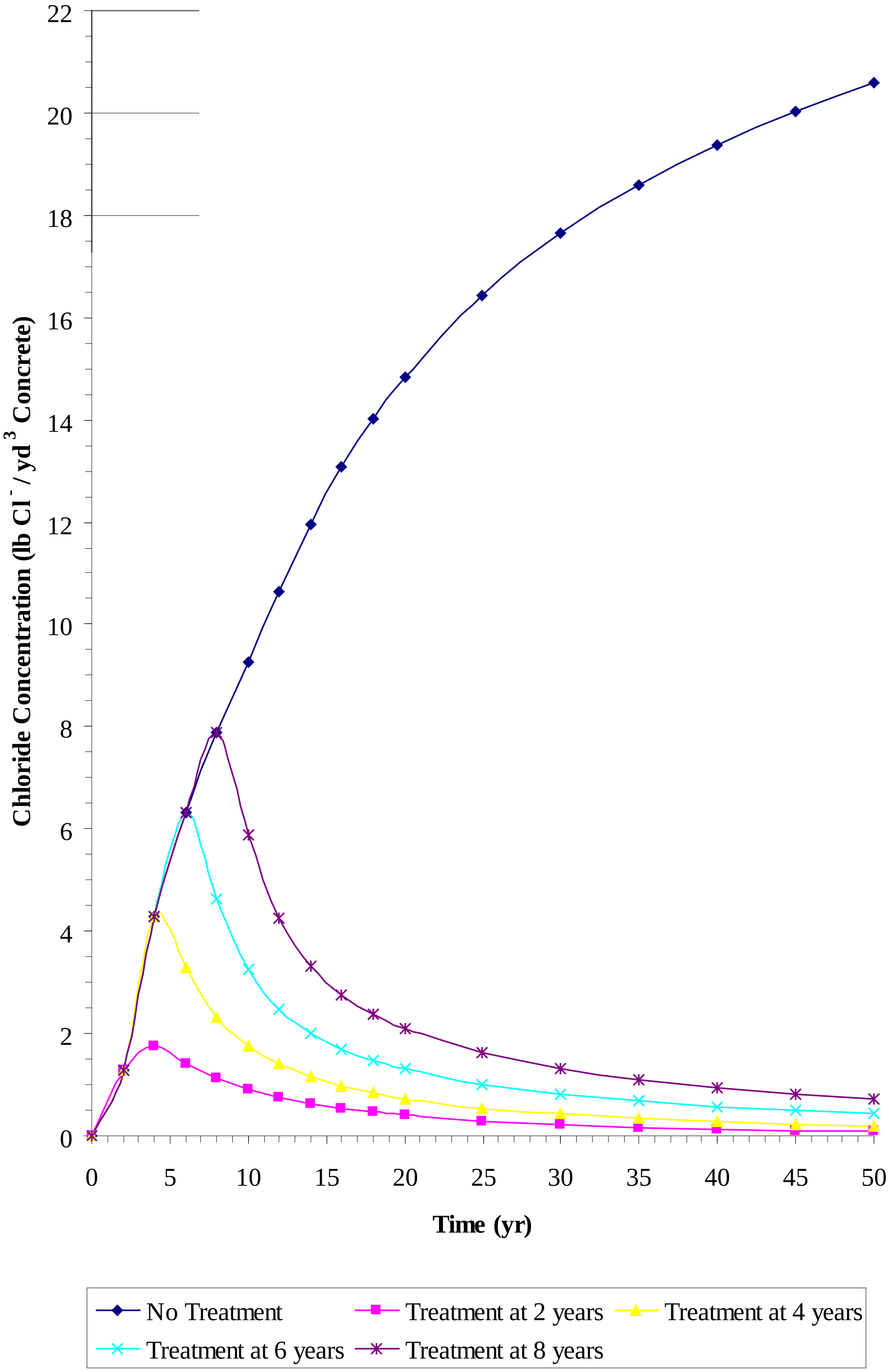

FIGURE A.2 Chloride concentrations of decks with SIPMFs with 2.0-in. OCD for 0.5-in. scarification and 2.0-in. overlay treatments.

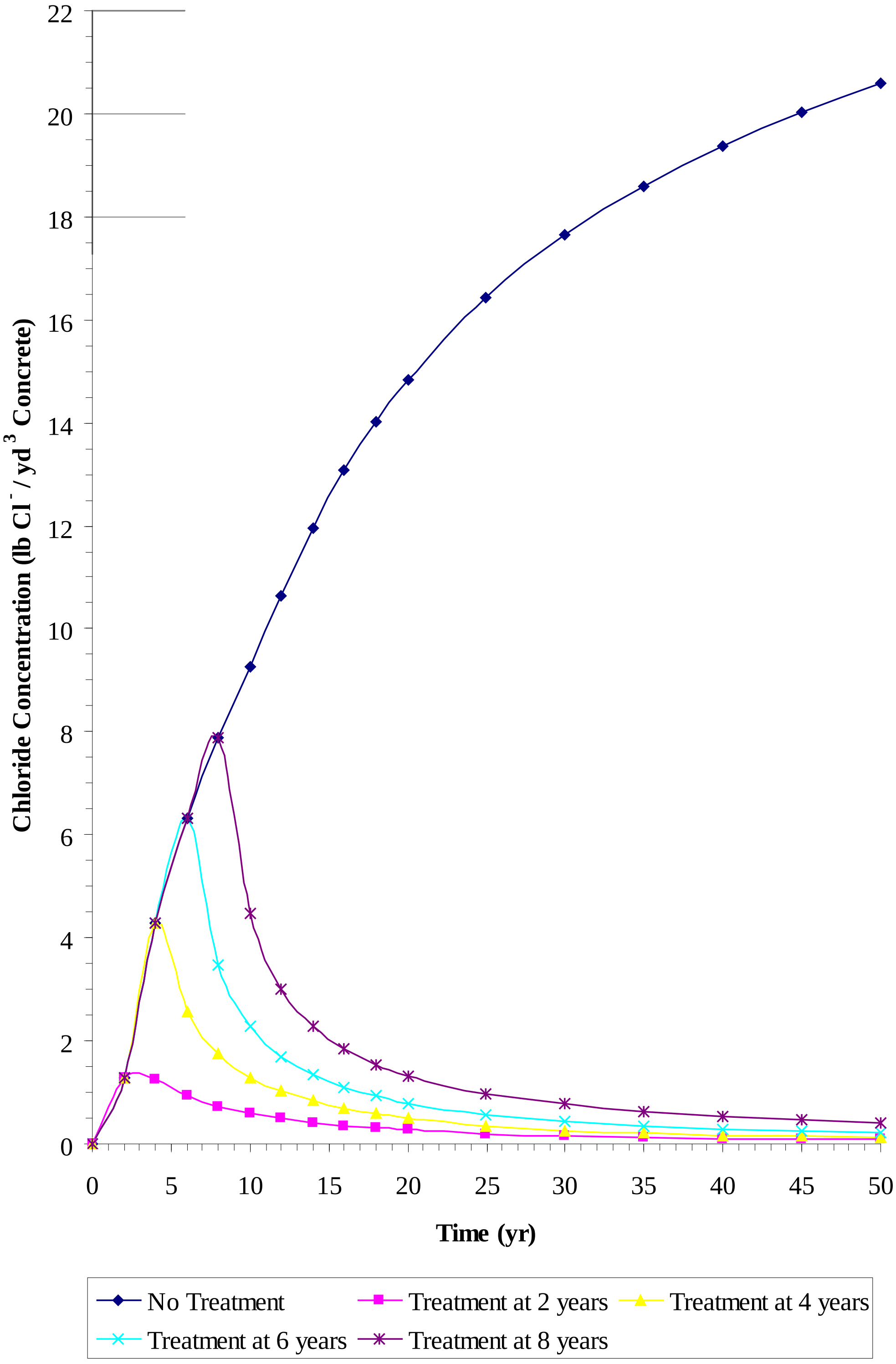

FIGURE A.3 Chloride concentrations of decks with SIPMFs with 2.0-in. OCD for 1.0-in. scarification and 1.5-in. overlay treatments.

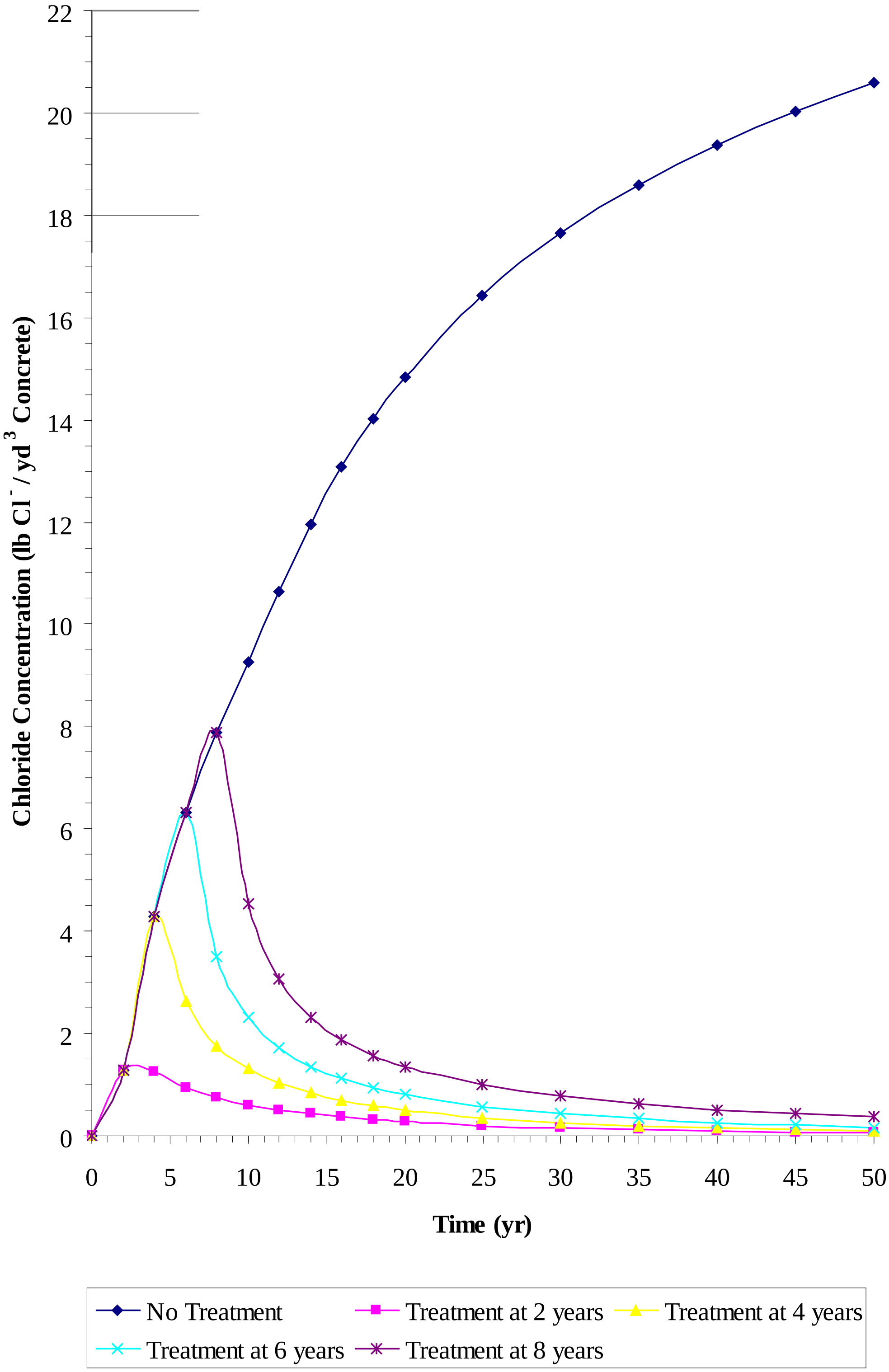

FIGURE A.4 Chloride concentrations of decks with SIPMFs with 2.0-in. OCD for 1.0-in. scarification and 2.0-in. overlay treatments.

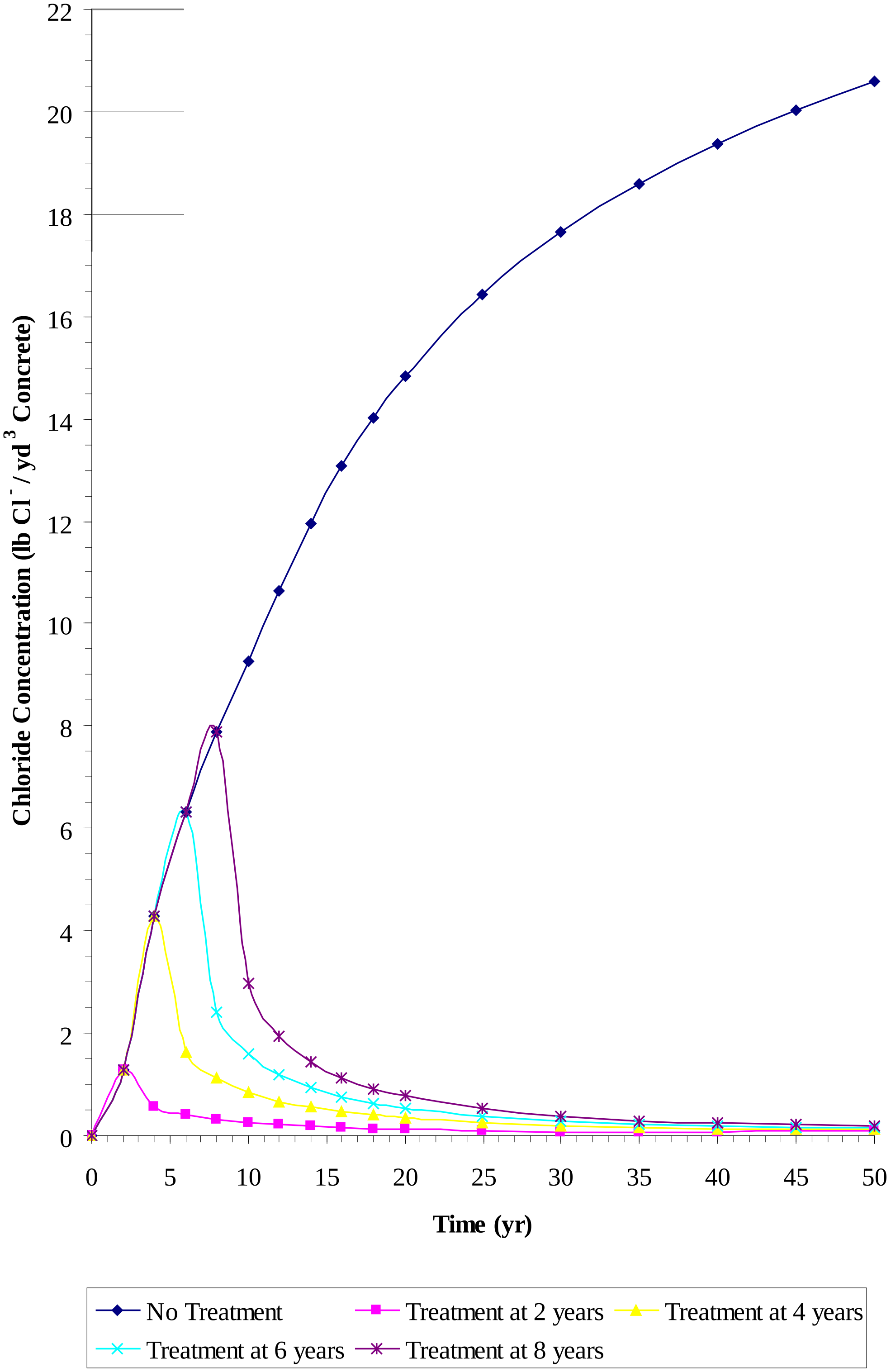

FIGURE A.5 Chloride concentrations of decks with SIPMFs with 2.0-in. OCD for 1.5-in. scarification and 1.5-in. overlay treatments.

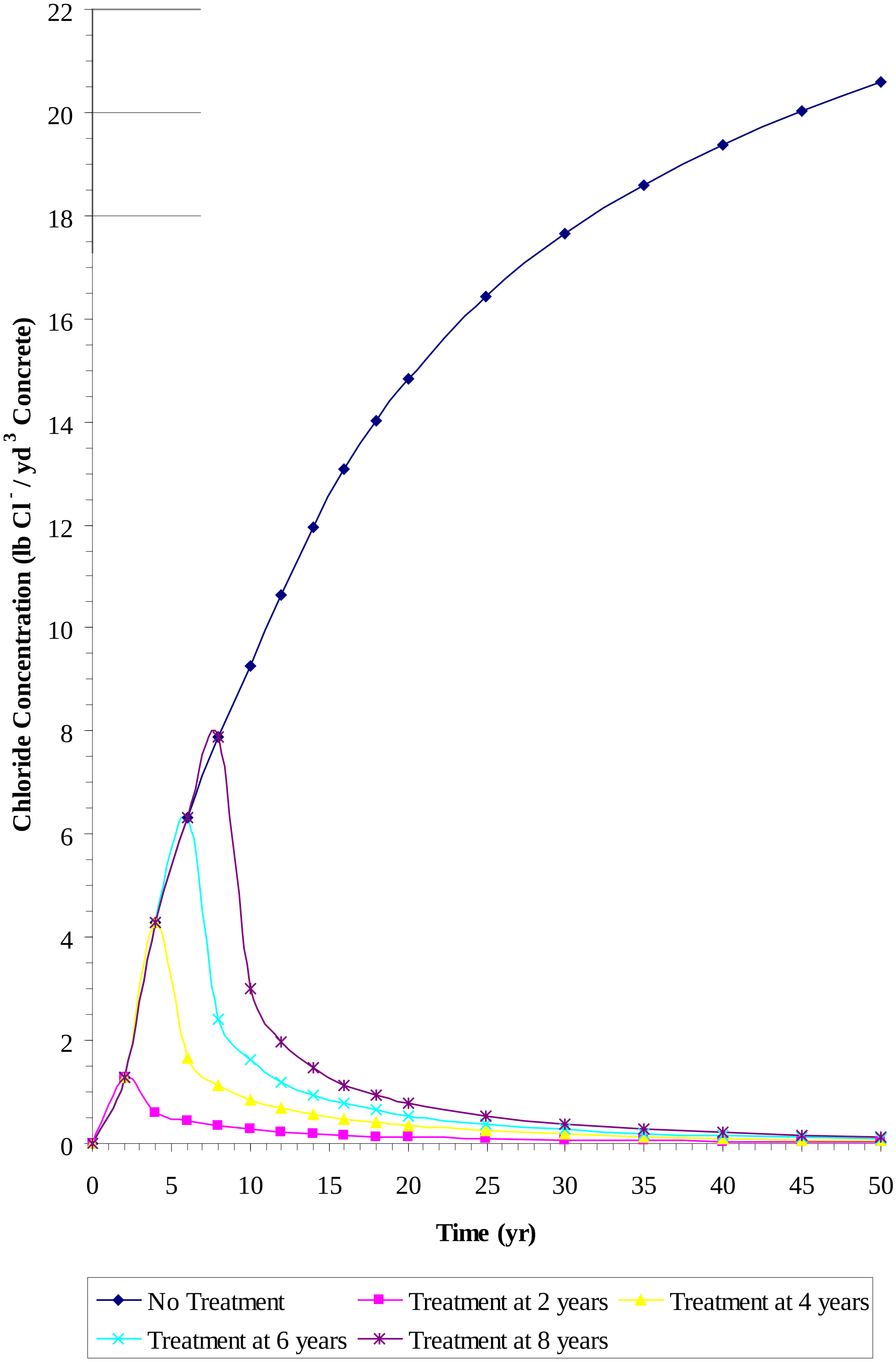

FIGURE A.6 Chloride concentrations of decks with SIPMFs with 2.0-in. OCD for 1.5-in. scarification and 2.0-in. overlay treatments.

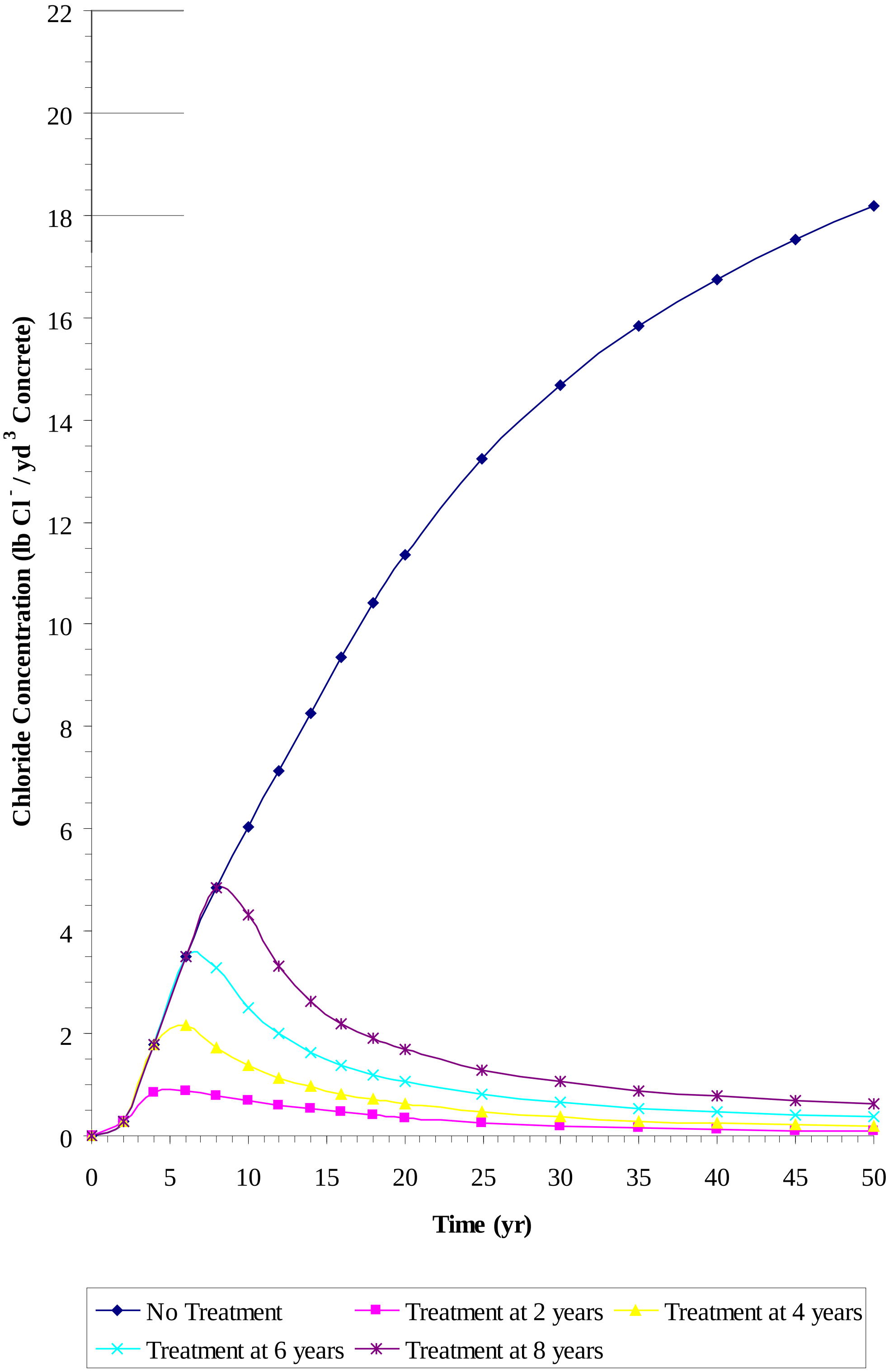

FIGURE A.7 Chloride concentrations of decks with SIPMFs with 2.5-in. OCD for 0.5-in. scarification and 1.5-in. overlay treatments.

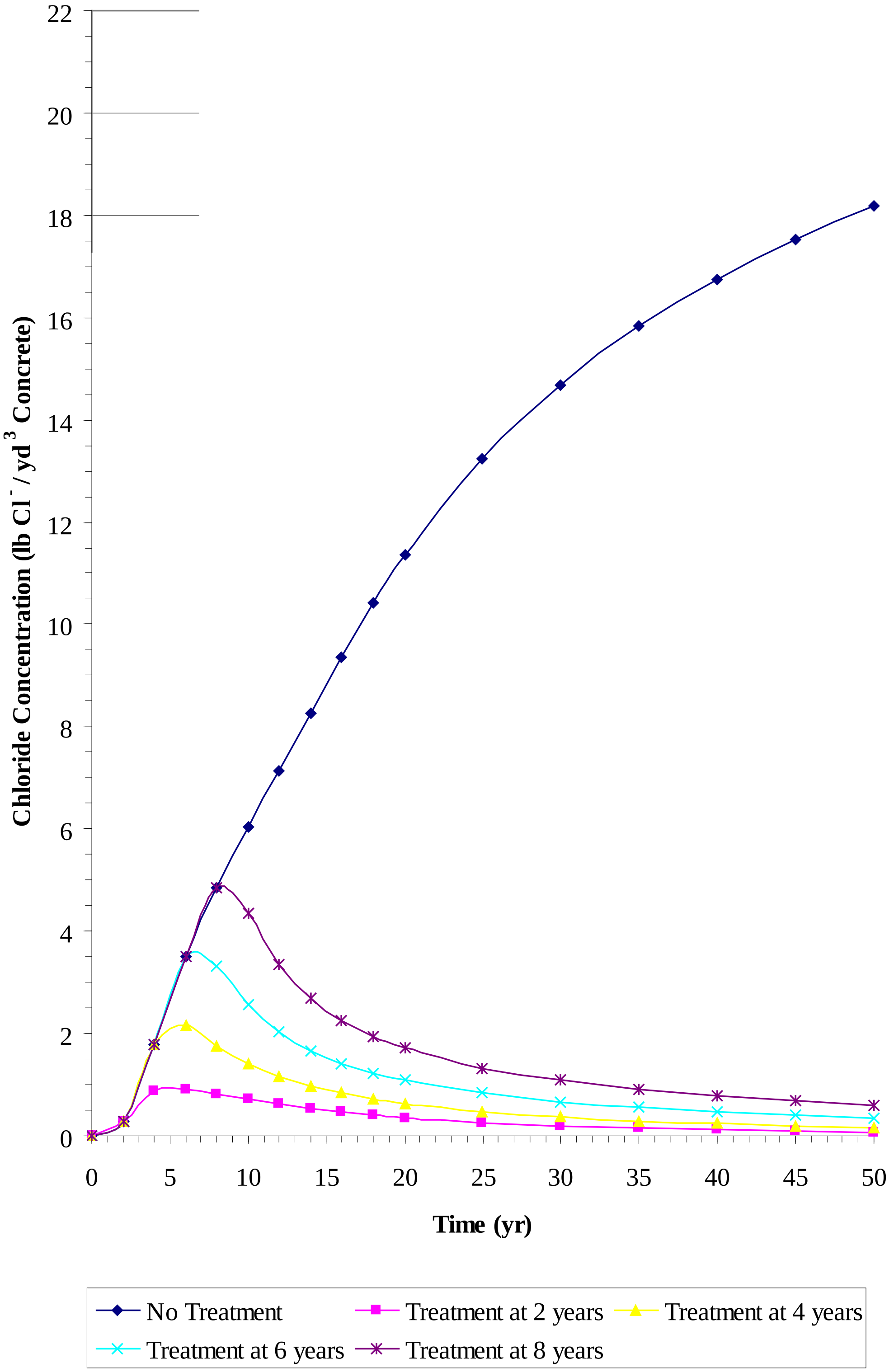

FIGURE A.8 Chloride concentrations of decks with SIPMFs with 2.5-in. OCD for 0.5-in. scarification and 2.0-in. overlay treatments.

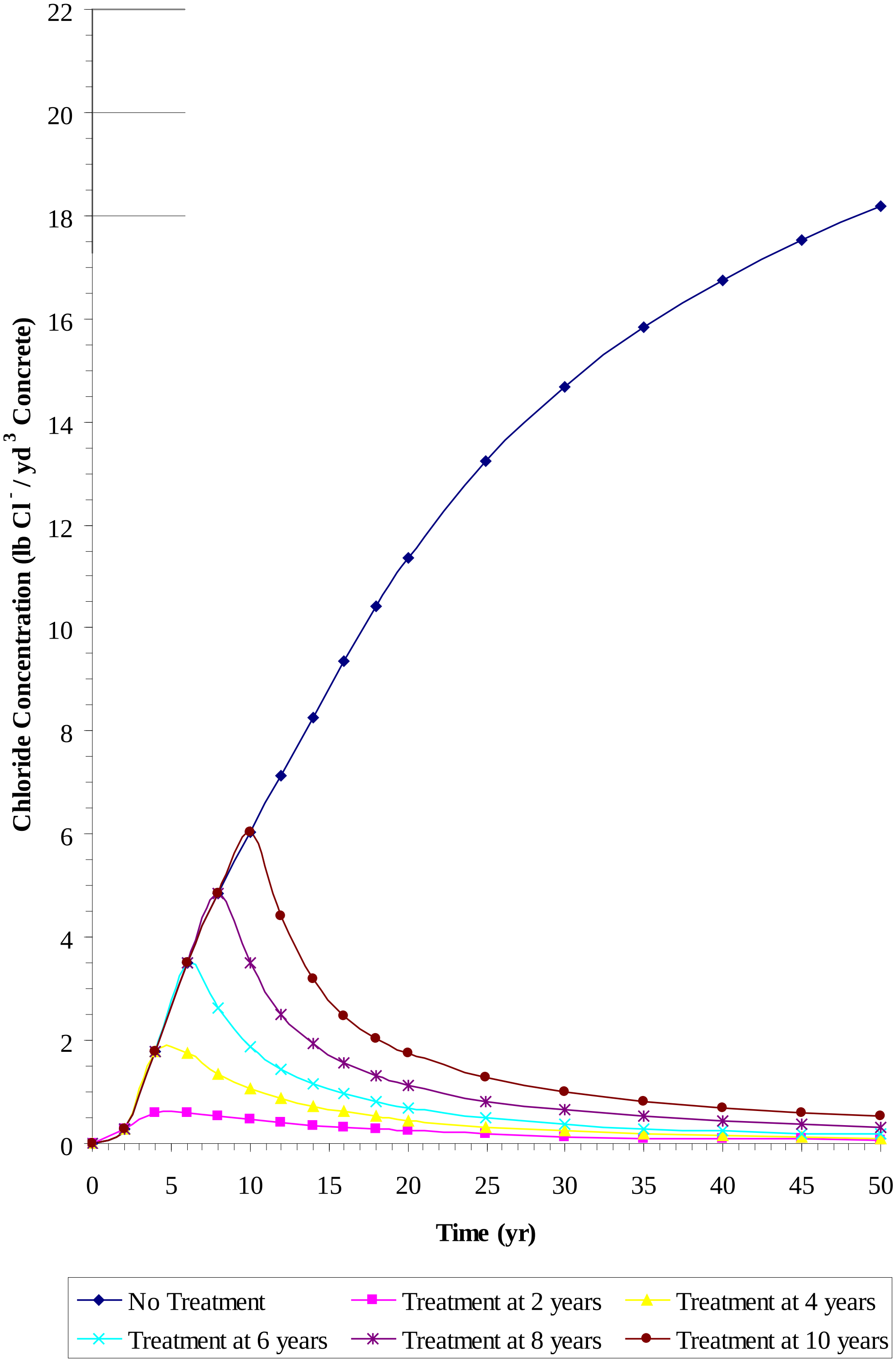

FIGURE A.9 Chloride concentrations of decks with SIPMFs with 2.5-in. OCD for 1.0-in. scarification and 1.5-in. overlay treatments.

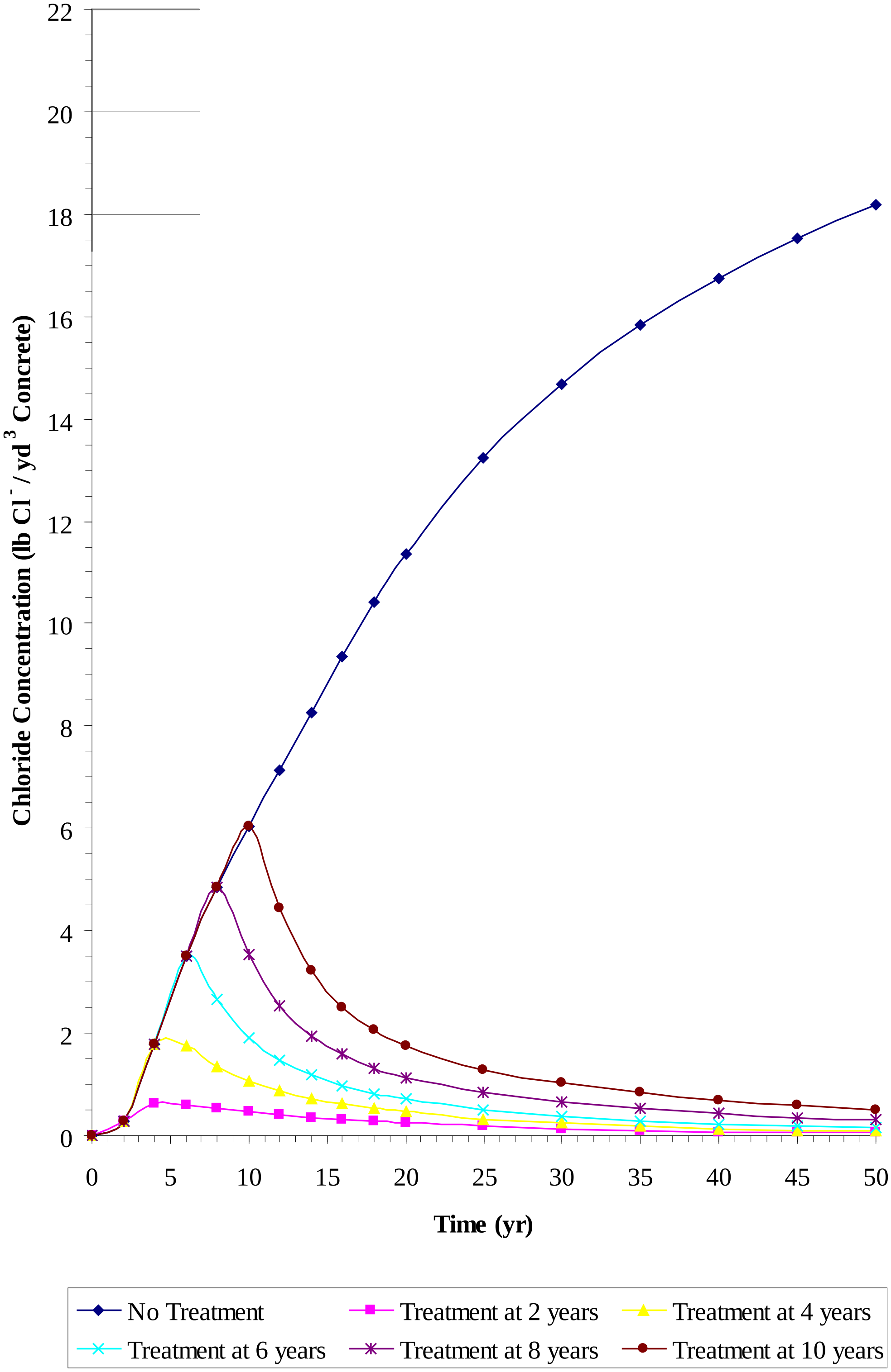

FIGURE A.10 Chloride concentrations of decks with SIPMFs with 2.5-in. OCD for 1.0-in. scarification and 2.0-in. overlay treatments.

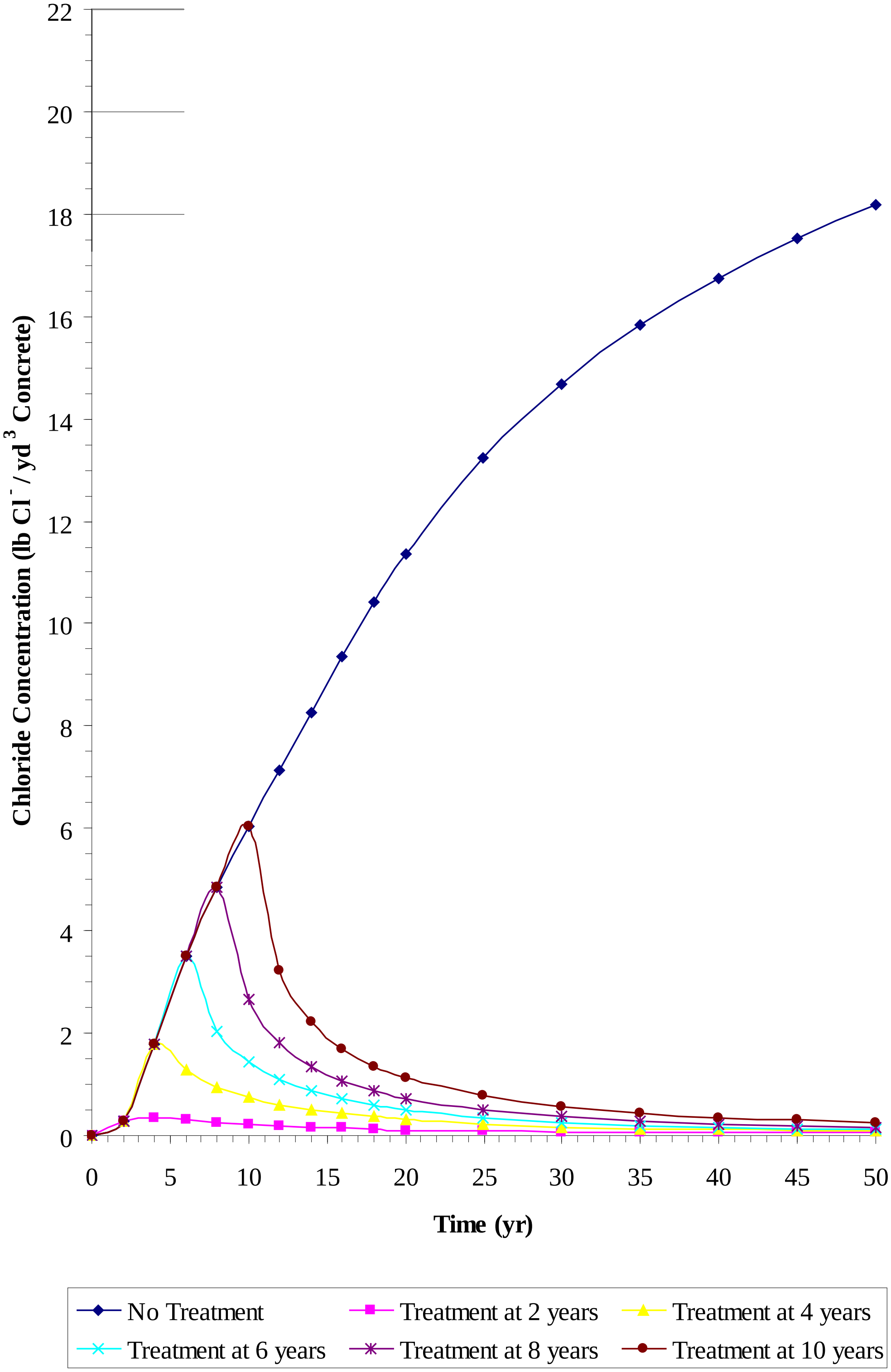

FIGURE A.11 Chloride concentrations of decks with SIPMFs with 2.5-in. OCD for 1.5-in. scarification and 1.5-in. overlay treatments.

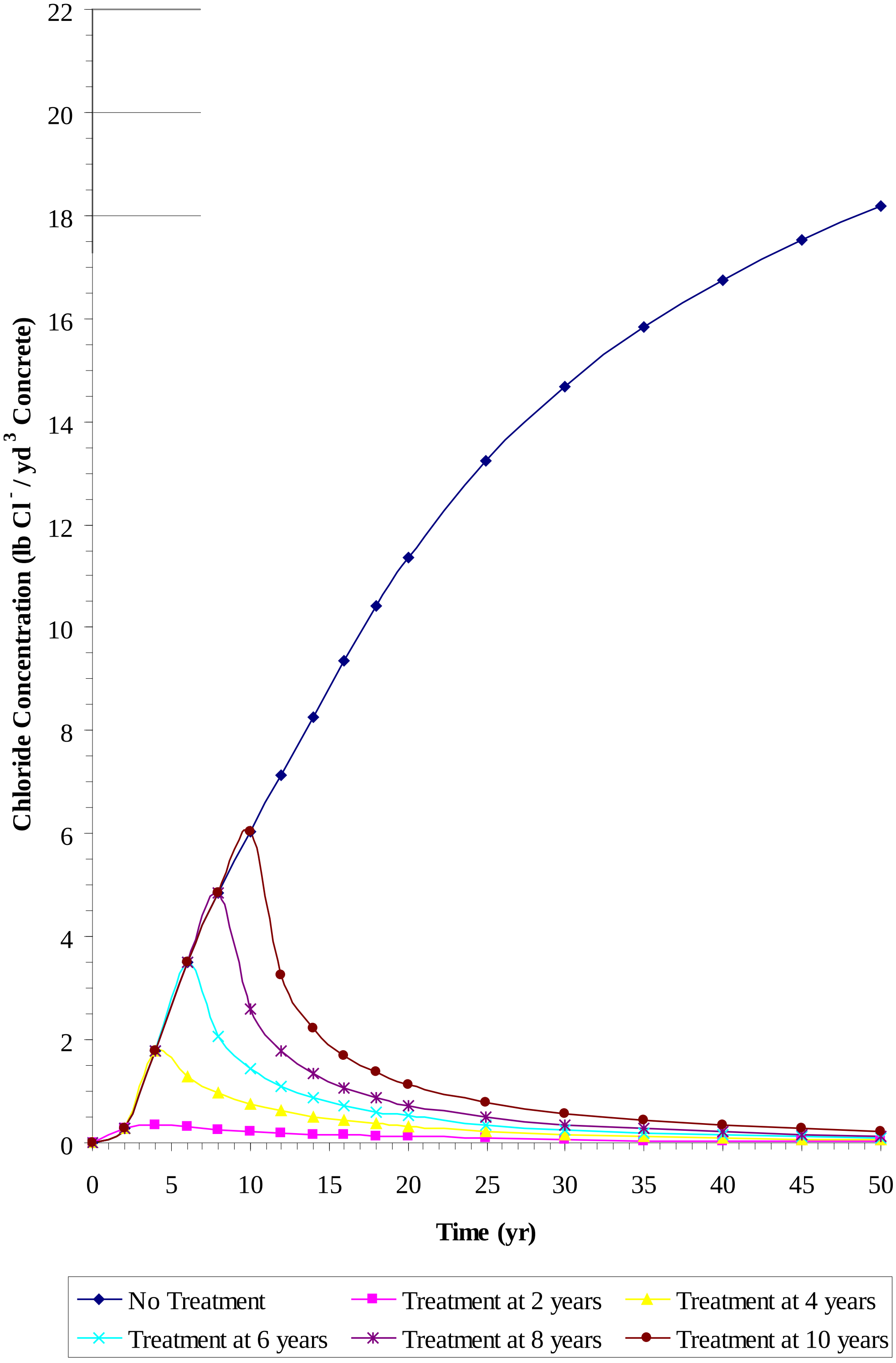

FIGURE A.12 Chloride concentrations of decks with SIPMFs with 2.5-in. OCD for 1.5-in. scarification and 2.0-in. overlay treatments.

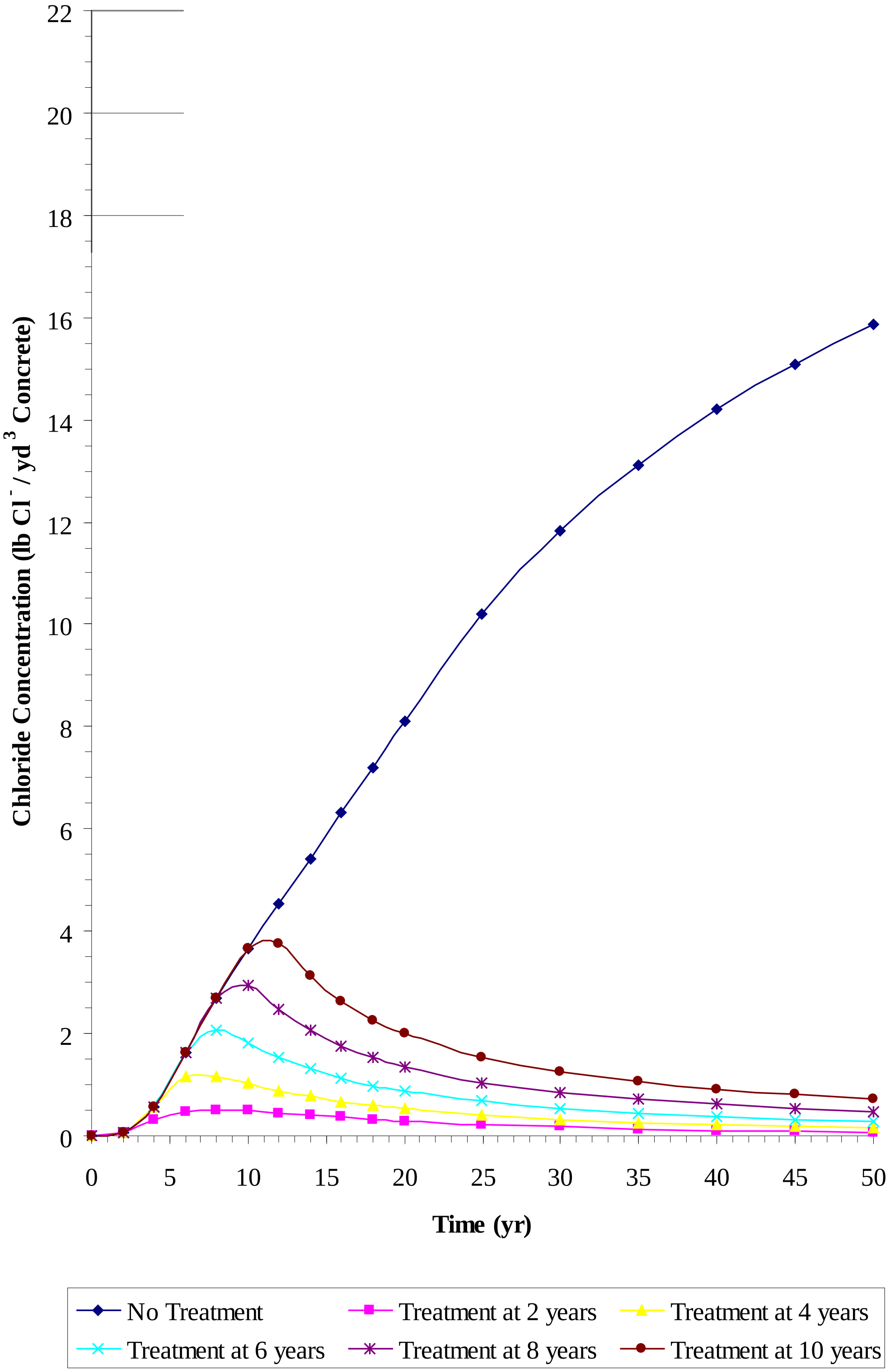

FIGURE A.13 Chloride concentrations of decks with SIPMFs with 3.0-in. OCD for 0.5-in. scarification and 1.5-in. overlay treatments.

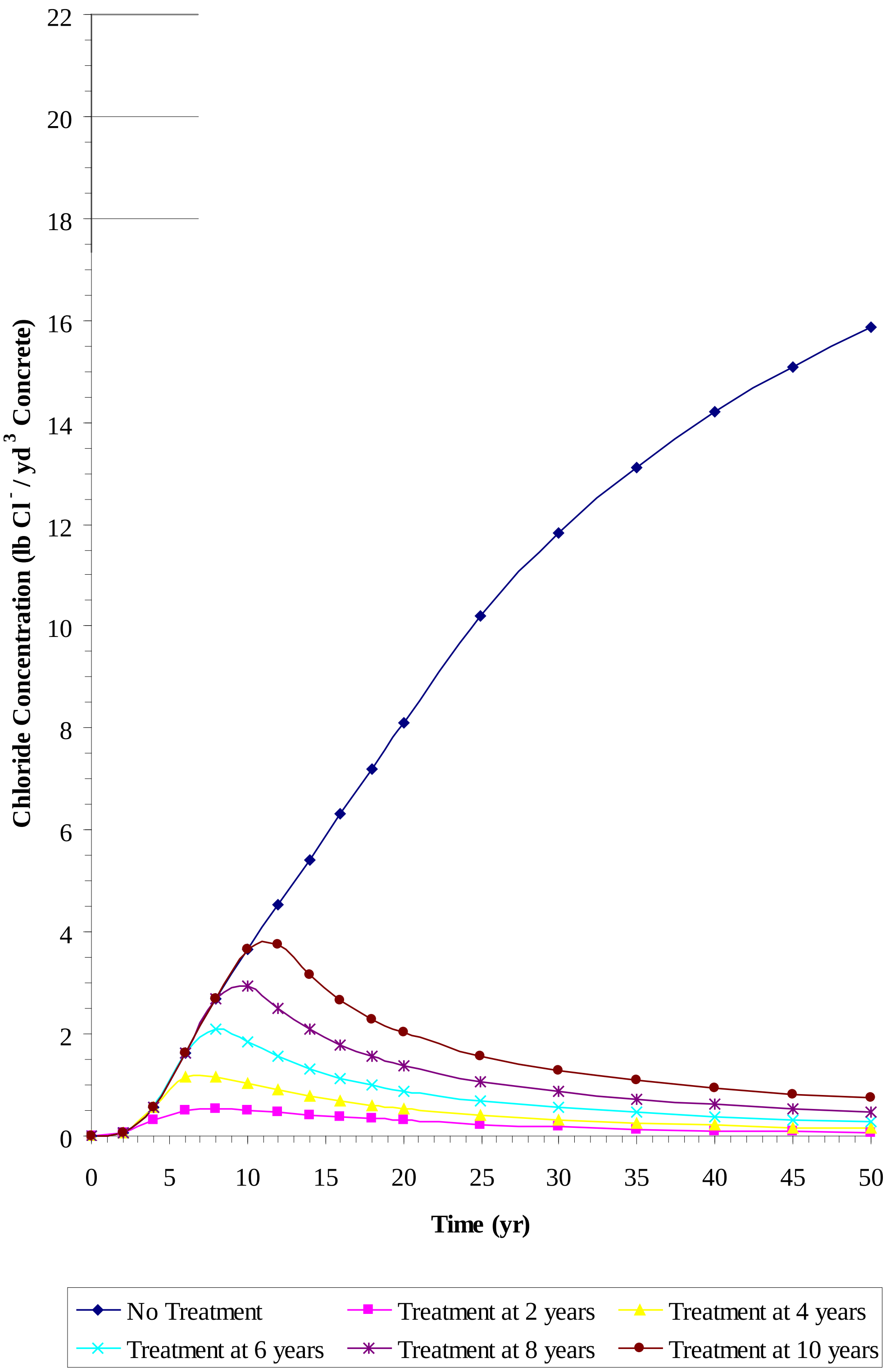

FIGURE A.14 Chloride concentrations of decks with SIPMFs with 3.0-in. OCD for 0.5-in. scarification and 2.0-in. overlay treatments.

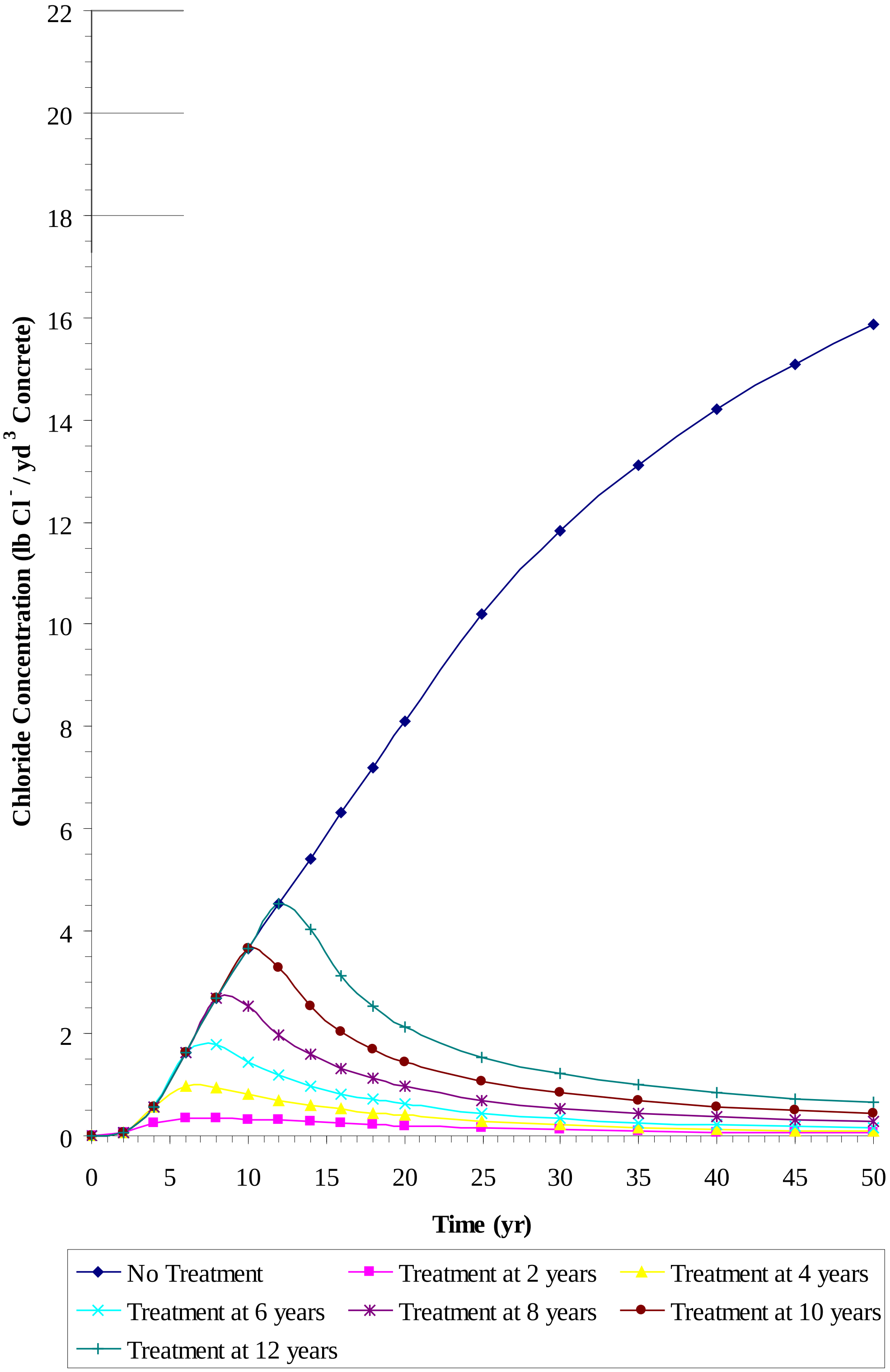

FIGURE A.15 Chloride concentrations of decks with SIPMFs with 3.0-in. OCD for 1.0-in. scarification and 1.5-in. overlay treatments.

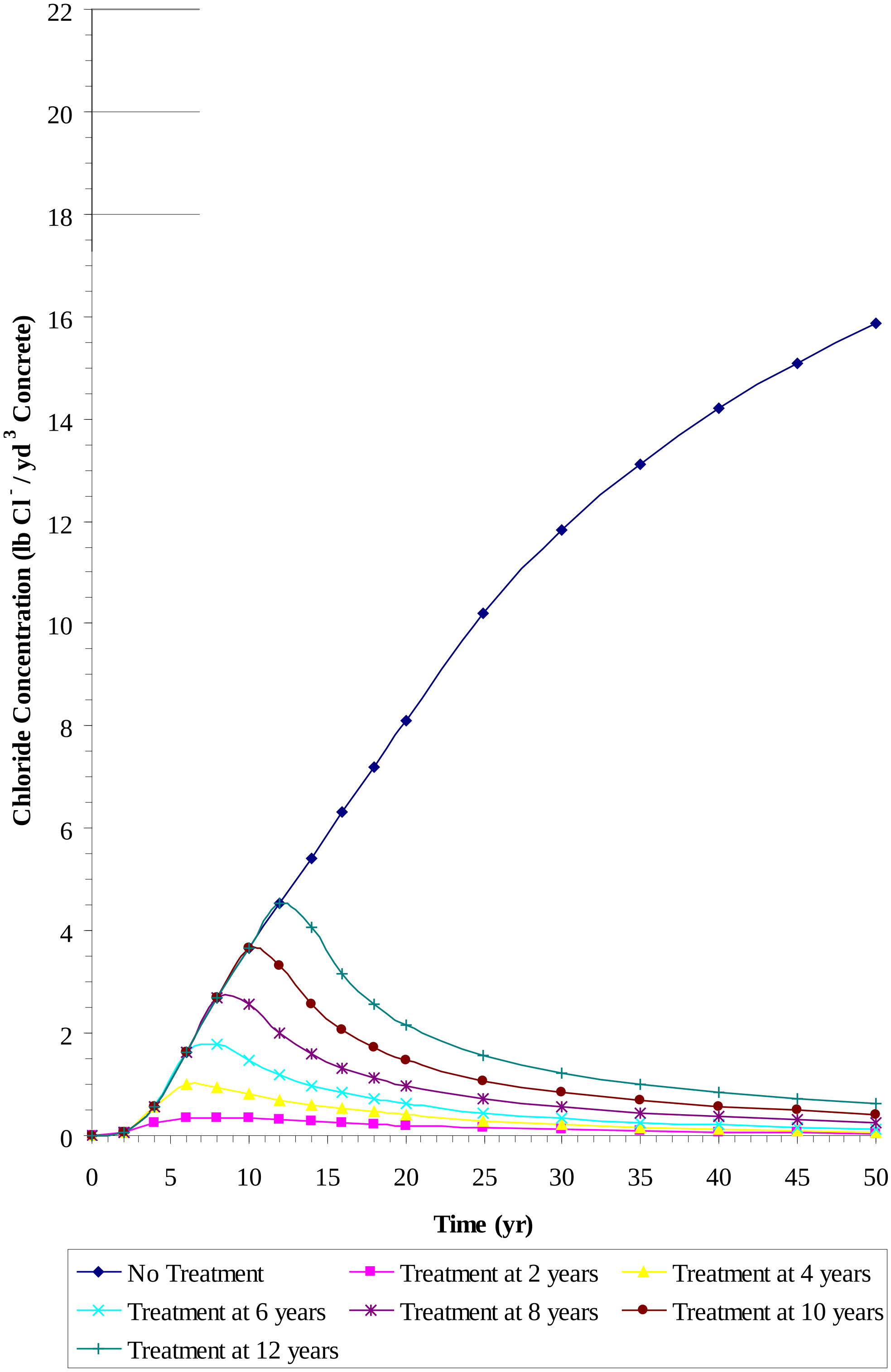

FIGURE A.16 Chloride concentrations of decks with SIPMFs with 3.0-in. OCD for 1.0-in. scarification and 2.0-in. overlay treatments.

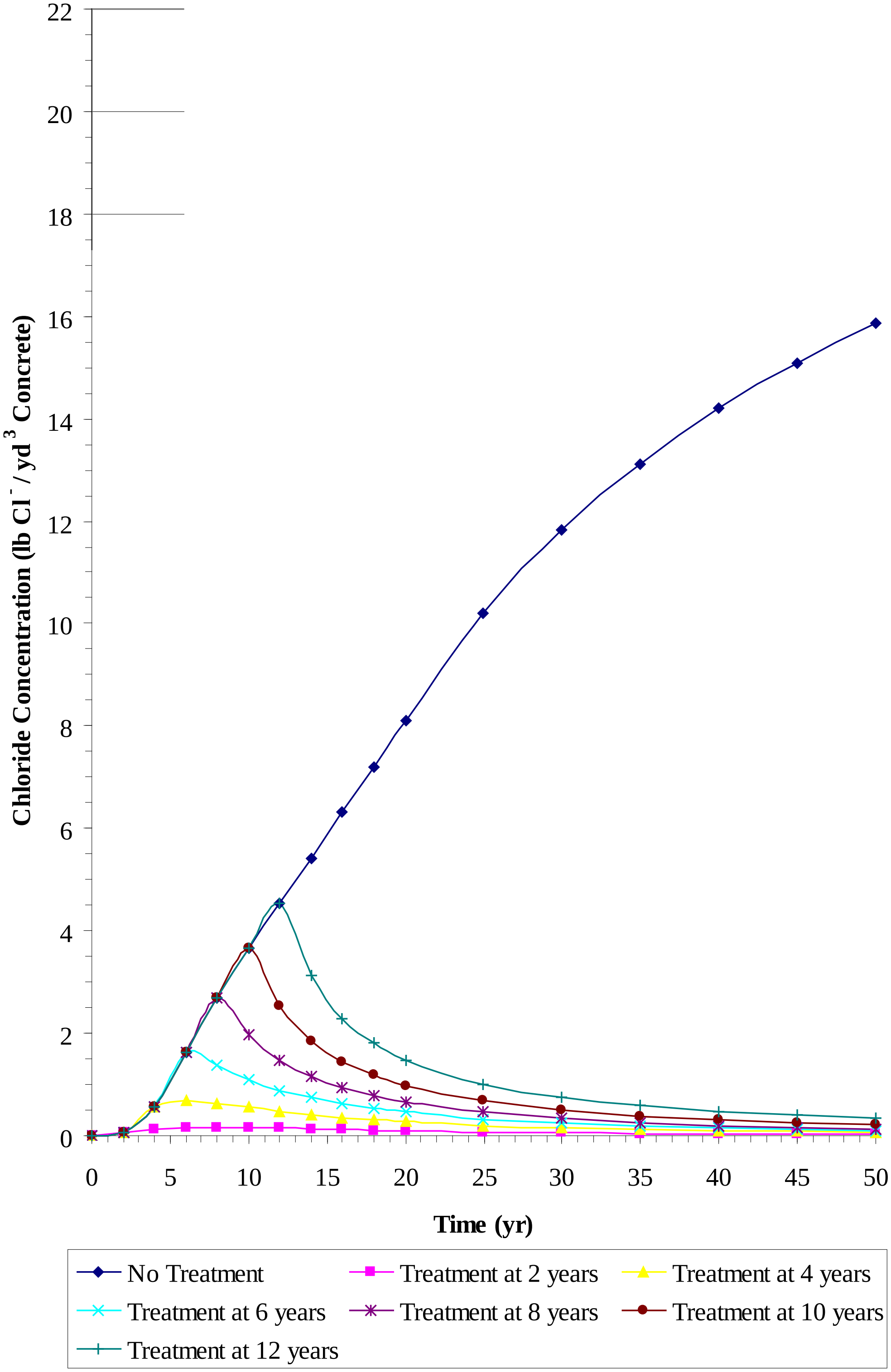

FIGURE A.17 Chloride concentrations of decks with SIPMFs with 3.0-in. OCD for 1.5-in. scarification and 1.5-in. overlay treatments.

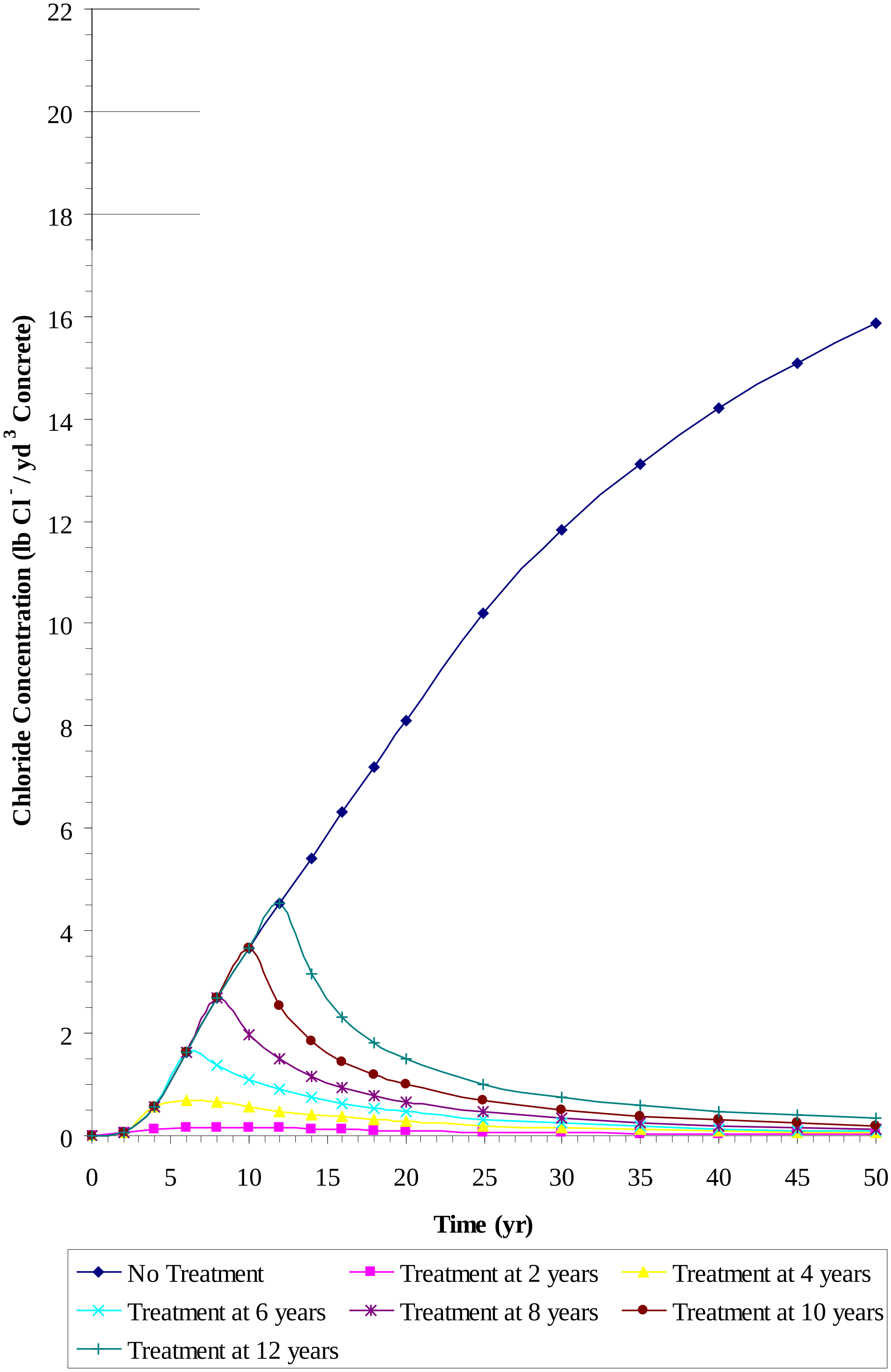

FIGURE A.18 Chloride concentrations of decks with SIPMFs with 3.0-in. OCD for 1.5-in. scarification and 2.0-in. overlay treatments.

APPENDIX B:

CHLORIDE CONCENTRATIONS AT LEVEL OF REINFORCING STEEL FOR DECKS WITHOUT STAY-IN-PLACE METAL FORMS

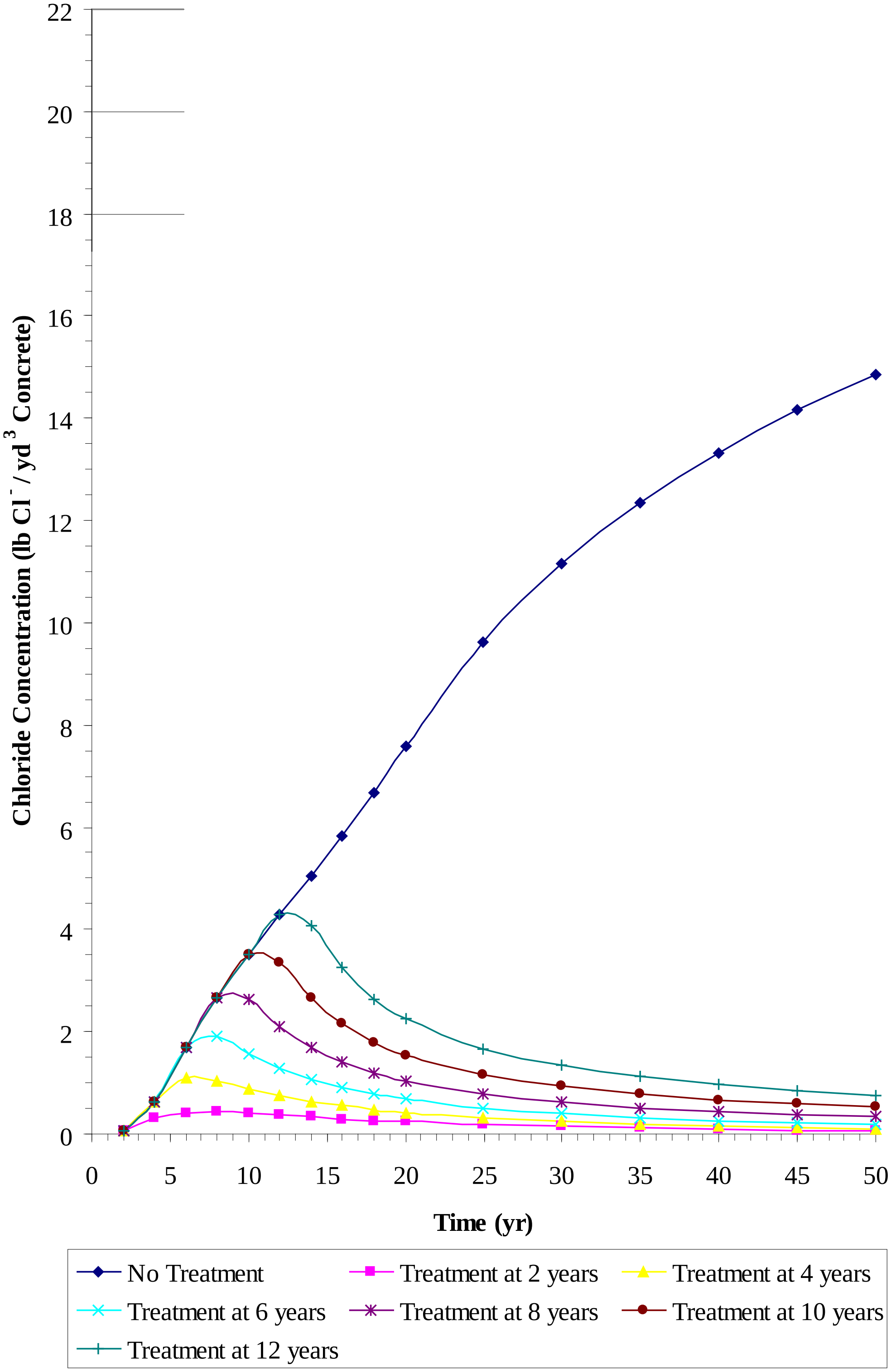

FIGURE B.1 Chloride concentrations of decks without SIPMFs with 2.0-in. OCD for 0.5-in. scarification and 1.5-in. overlay treatments.

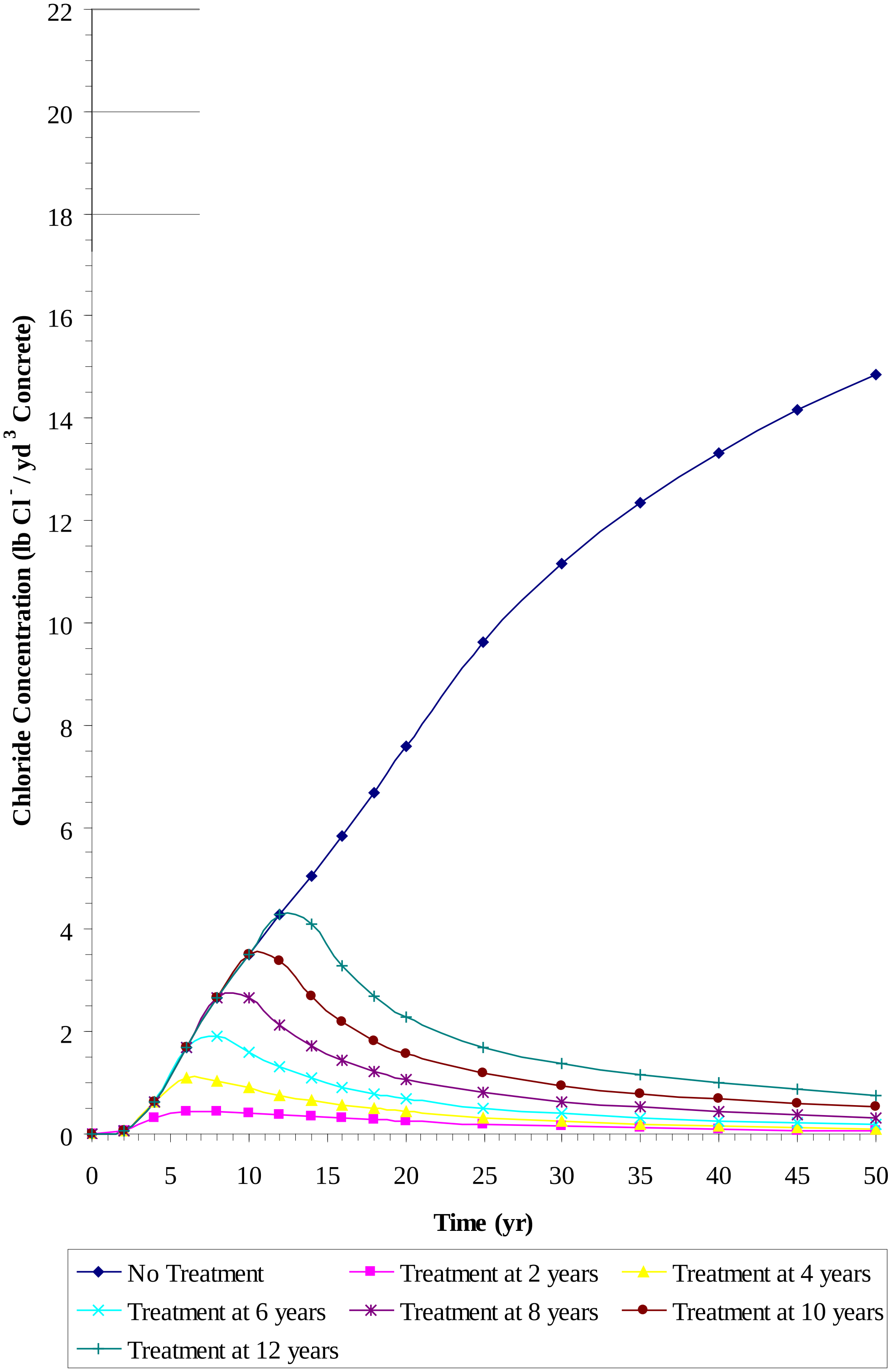

FIGURE B.2 Chloride concentrations of decks without SIPMFs with 2.0-in. OCD for 0.5-in. scarification and 2.0-in. overlay treatments.

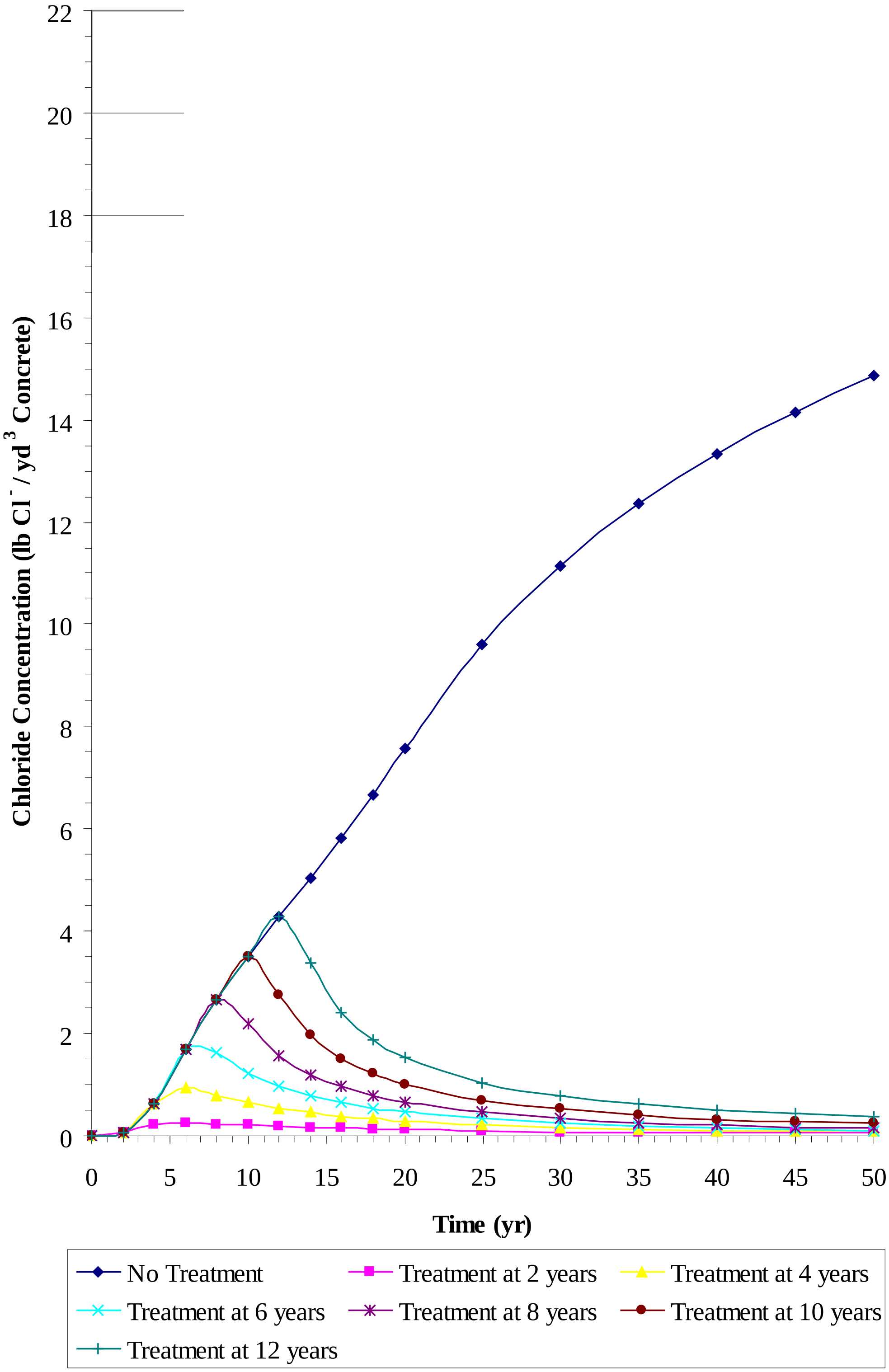

FIGURE B.3 Chloride concentrations of decks without SIPMFs with 2.0-in. OCD for 1.0-in. scarification and 1.5-in. overlay treatments.

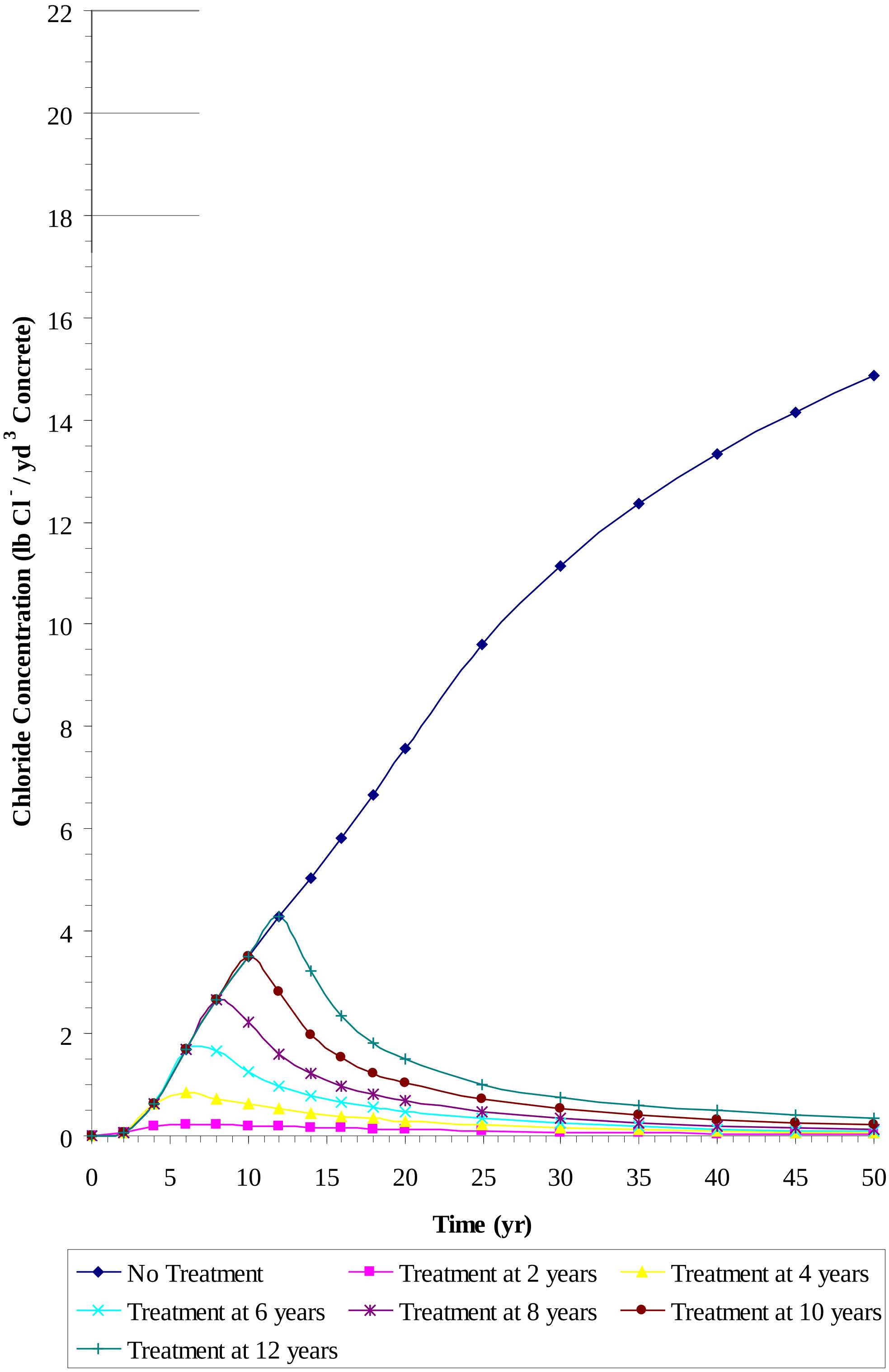

FIGURE B.4 Chloride concentrations of decks without SIPMFs with 2.0-in. OCD for 1.0-in. scarification and 2.0-in. overlay treatments.

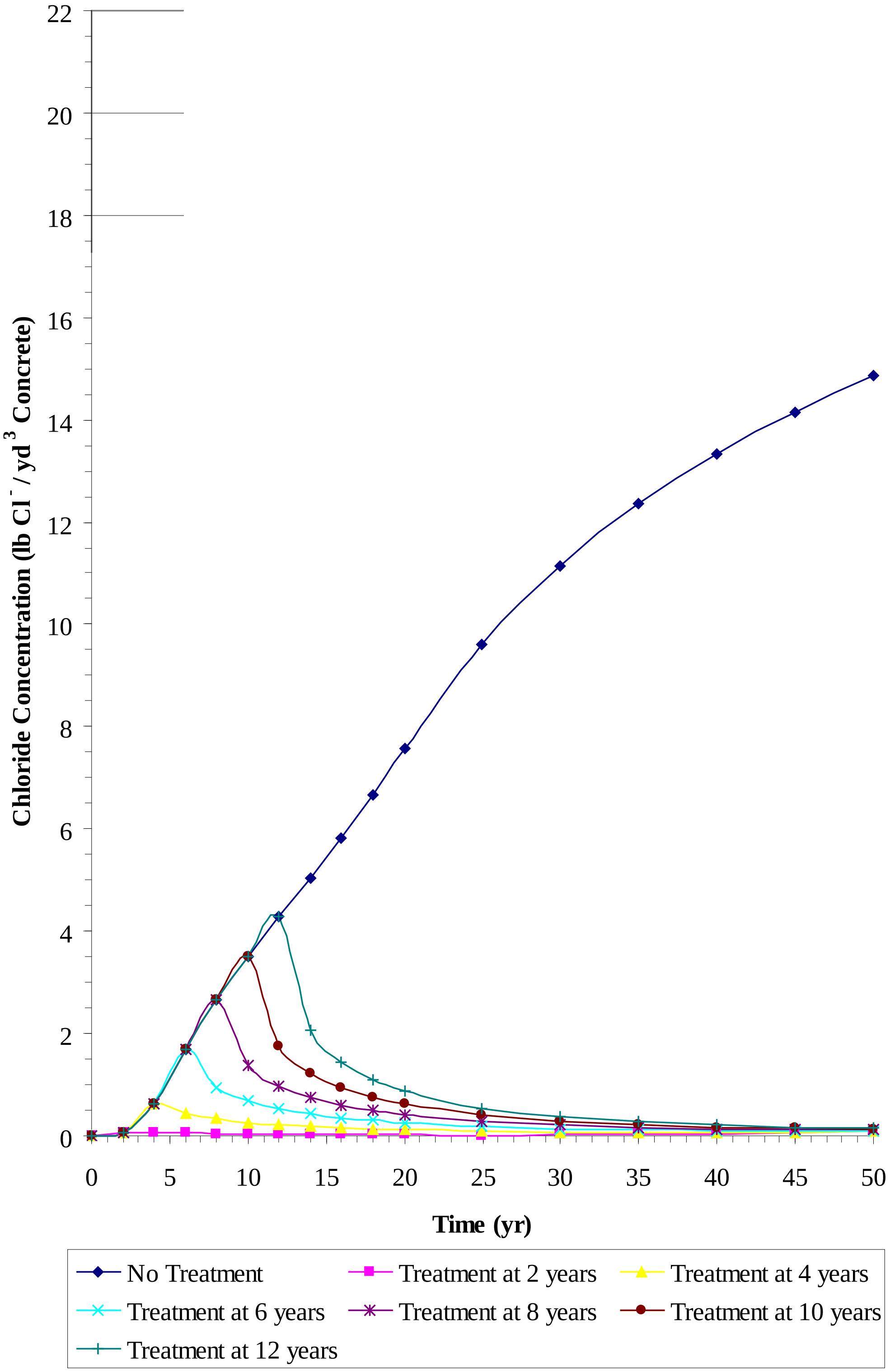

FIGURE B.5 Chloride concentrations of decks without SIPMFs with 2.0-in. OCD for 1.5-in. scarification and 1.5-in. overlay treatments.

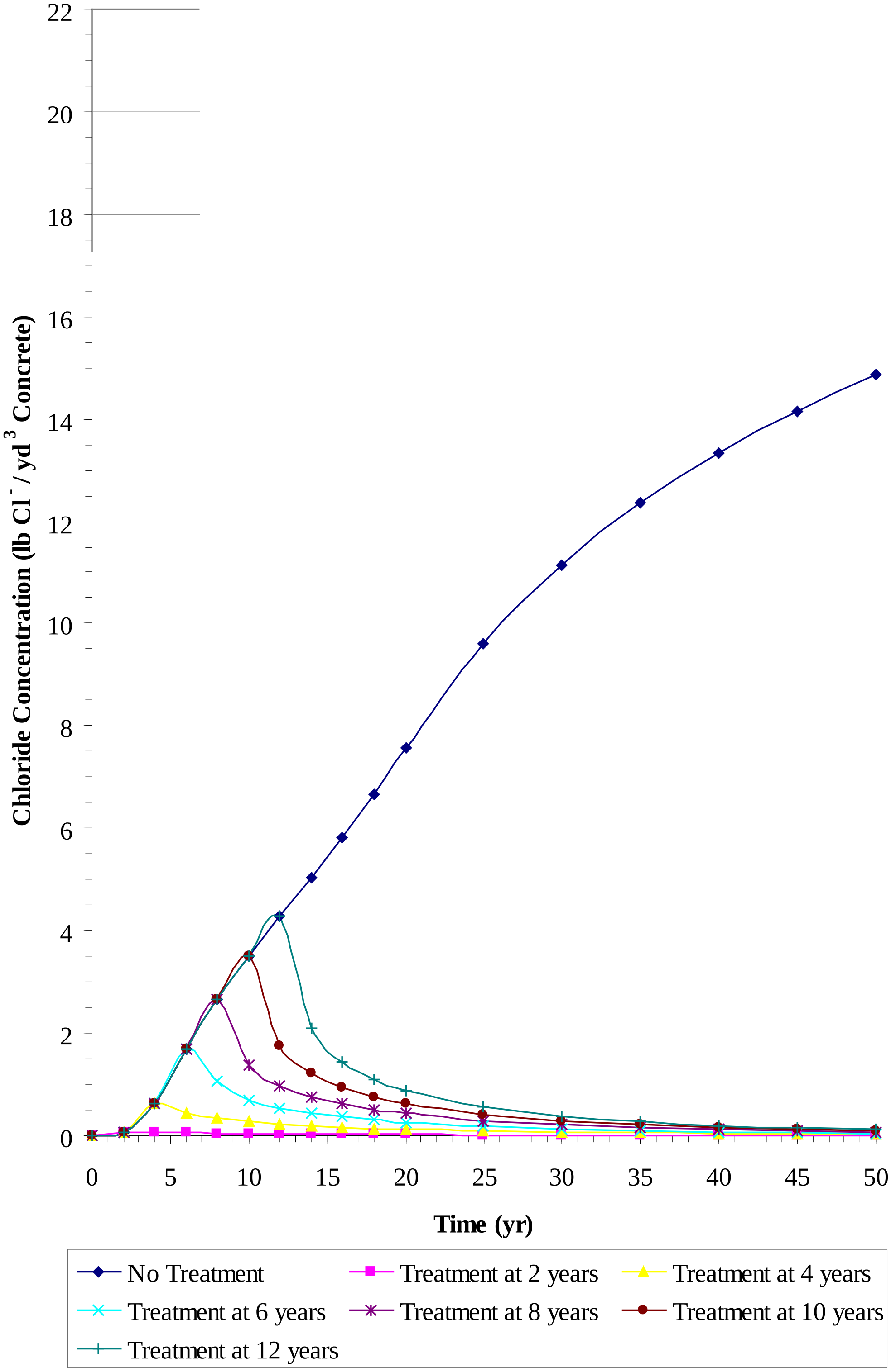

FIGURE B.6 Chloride concentrations of decks without SIPMFs with 2.0-in. OCD for 1.5-in. scarification and 2.0-in. overlay treatments.

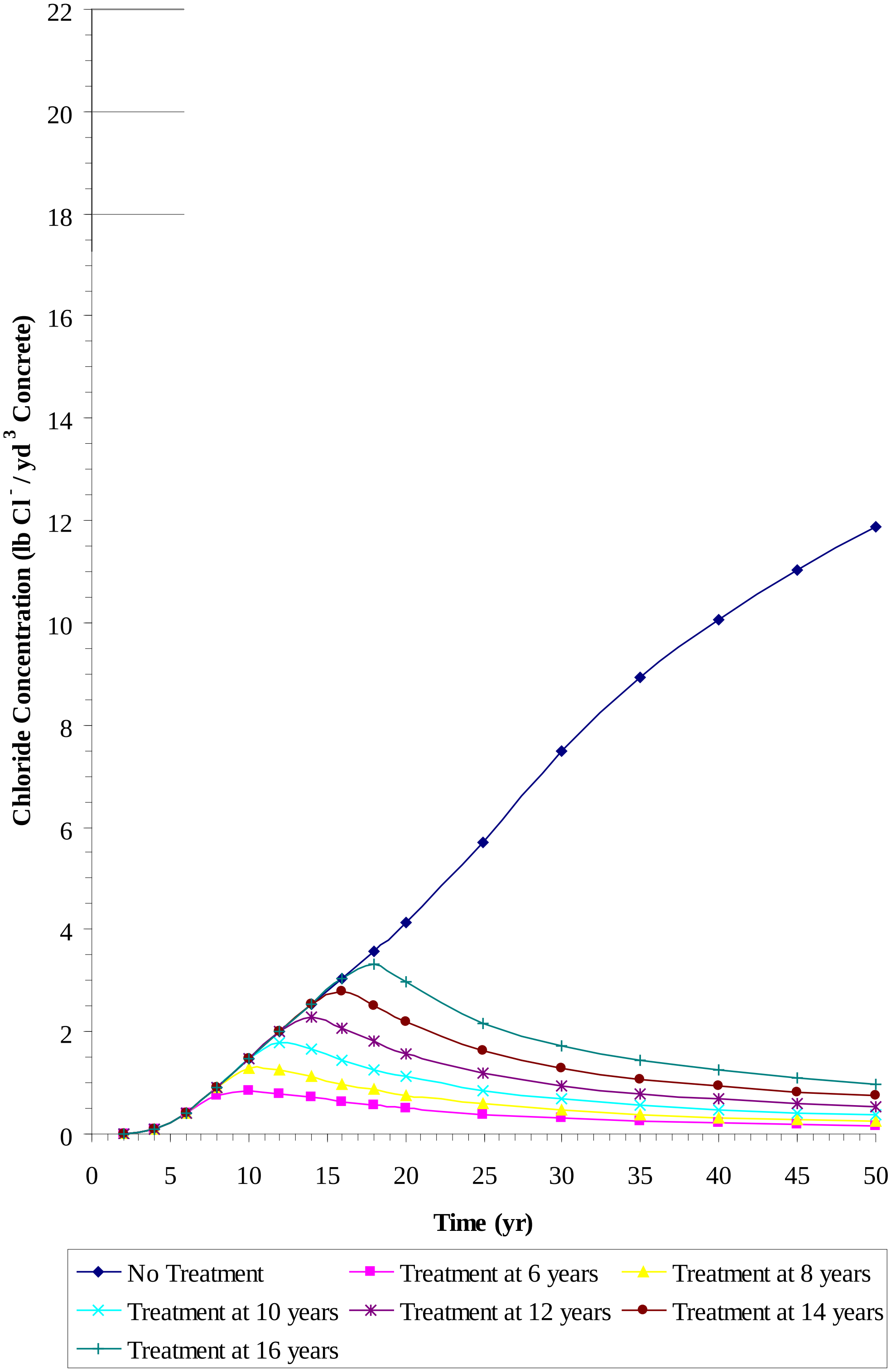

FIGURE B.7 Chloride concentrations of decks without SIPMFs with 2.5-in. OCD for 0.5-in. scarification and 1.5-in. overlay treatments.

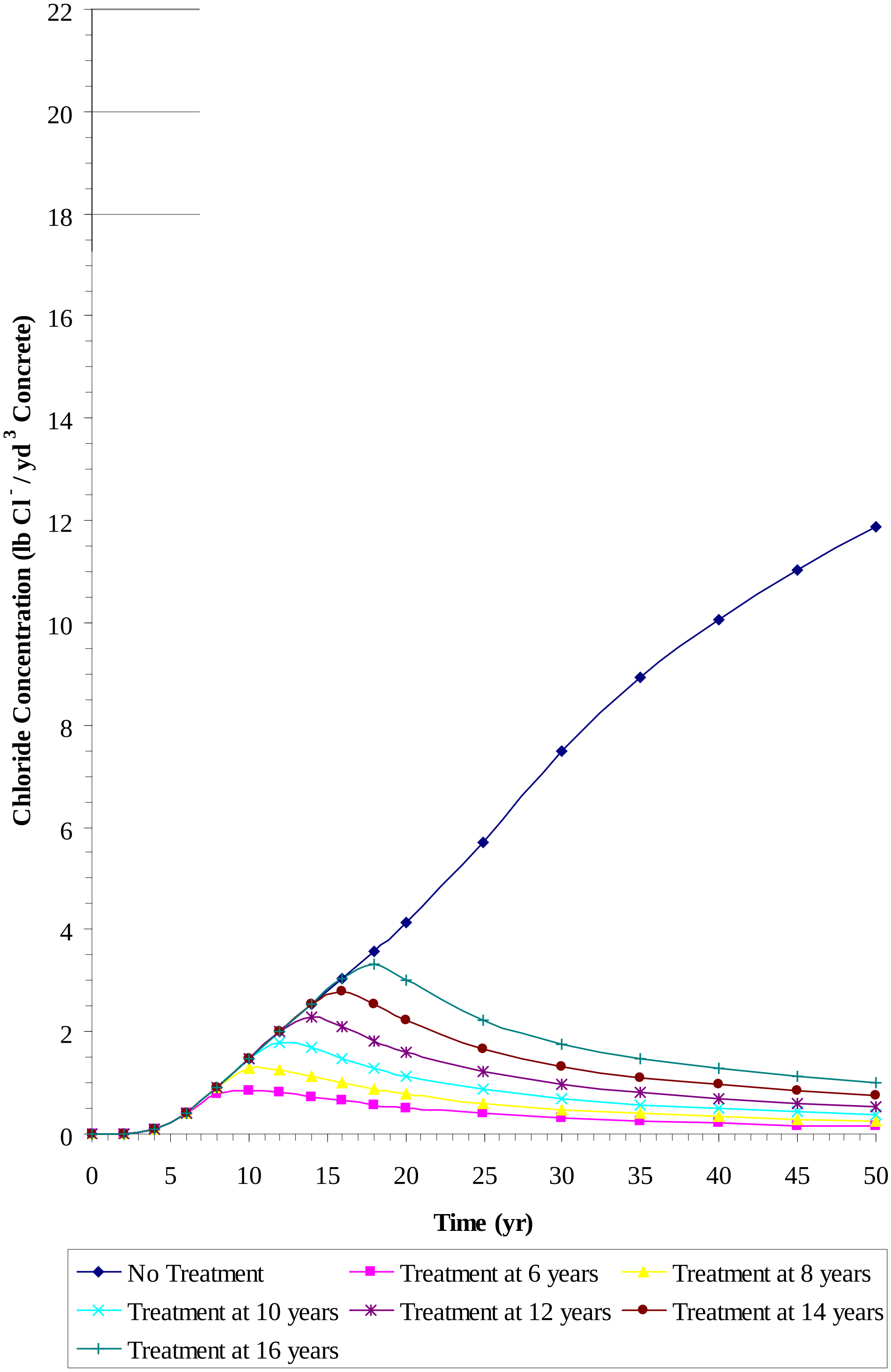

FIGURE B.8 Chloride concentrations of decks without SIPMFs with 2.5-in. OCD for 0.5-in. scarification and 2.0-in. overlay treatments.

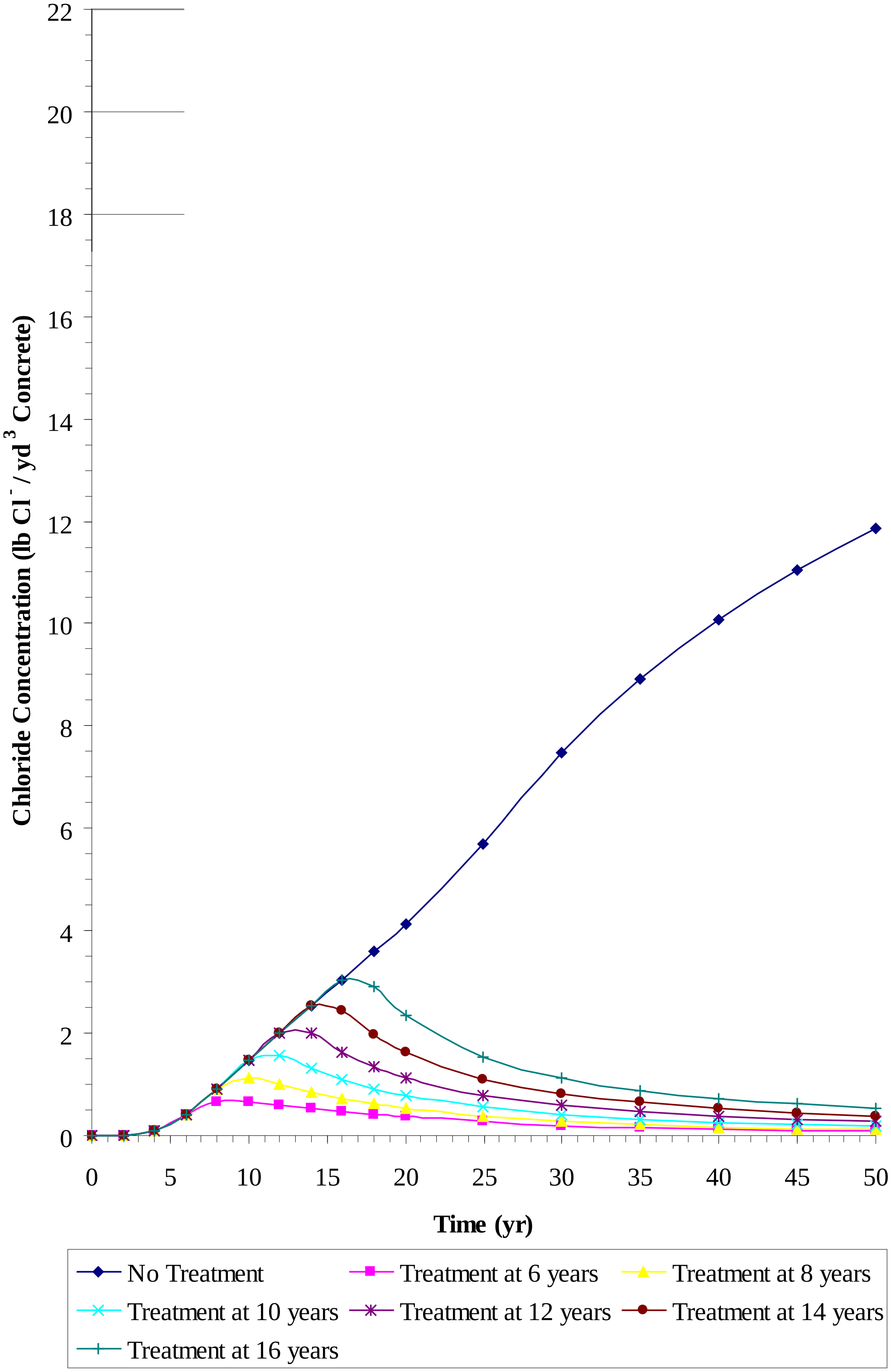

FIGURE B.9 Chloride concentrations of decks without SIPMFs with 2.5-in. OCD for 1.0-in. scarification and 1.5-in. overlay treatments.

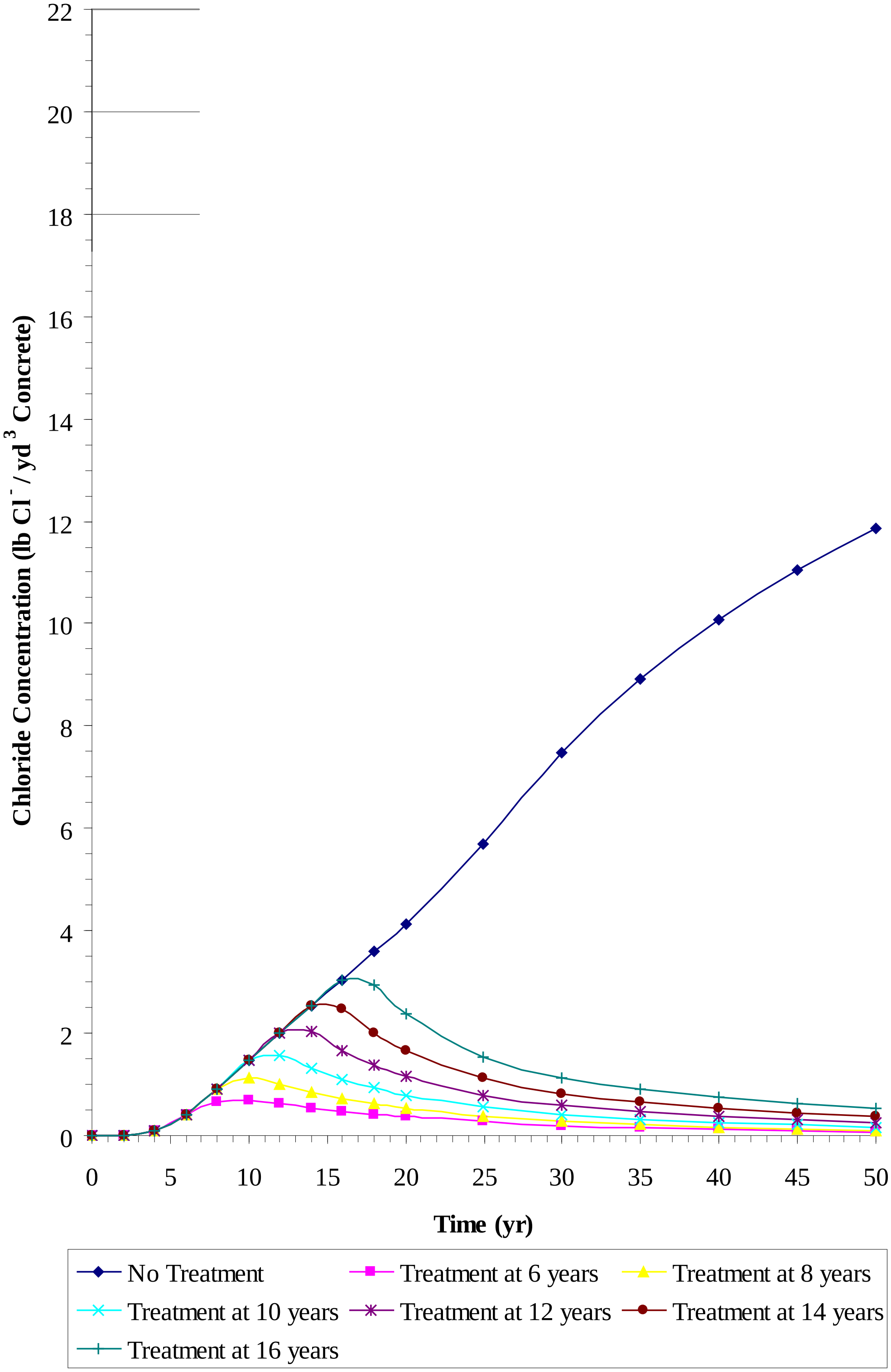

FIGURE B.10 Chloride concentrations of decks without SIPMFs with 2.5-in. OCD for 1.0-in. scarification and 2.0-in. overlay treatments.

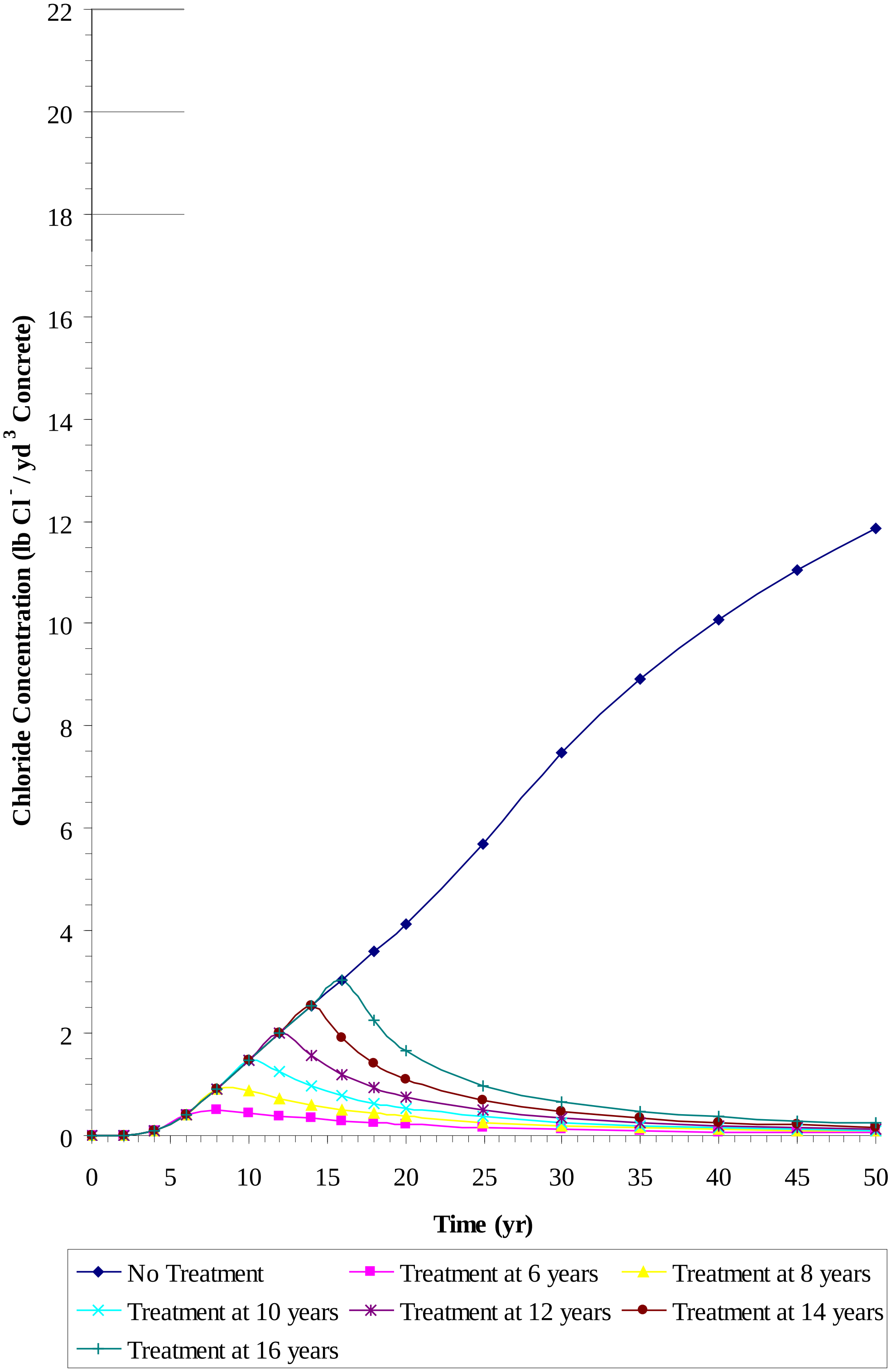

FIGURE B.11 Chloride concentrations of decks without SIPMFs with 2.5-in. OCD for 1.5-in. scarification and 1.5-in. overlay treatments.

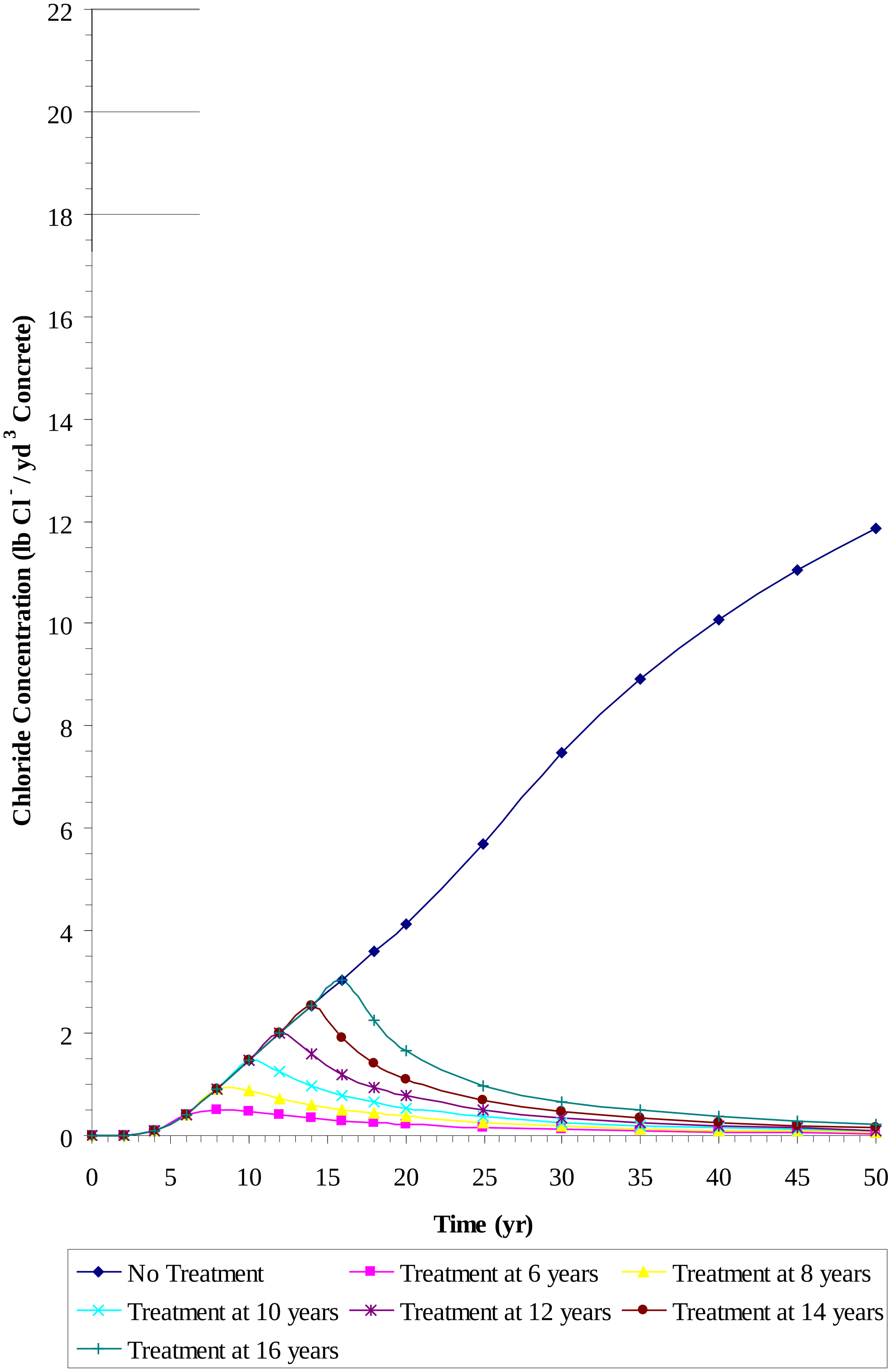

FIGURE B.12 Chloride concentrations of decks without SIPMFs with 2.5-in. OCD for 1.5-in. scarification and 2.0-in. overlay treatments.

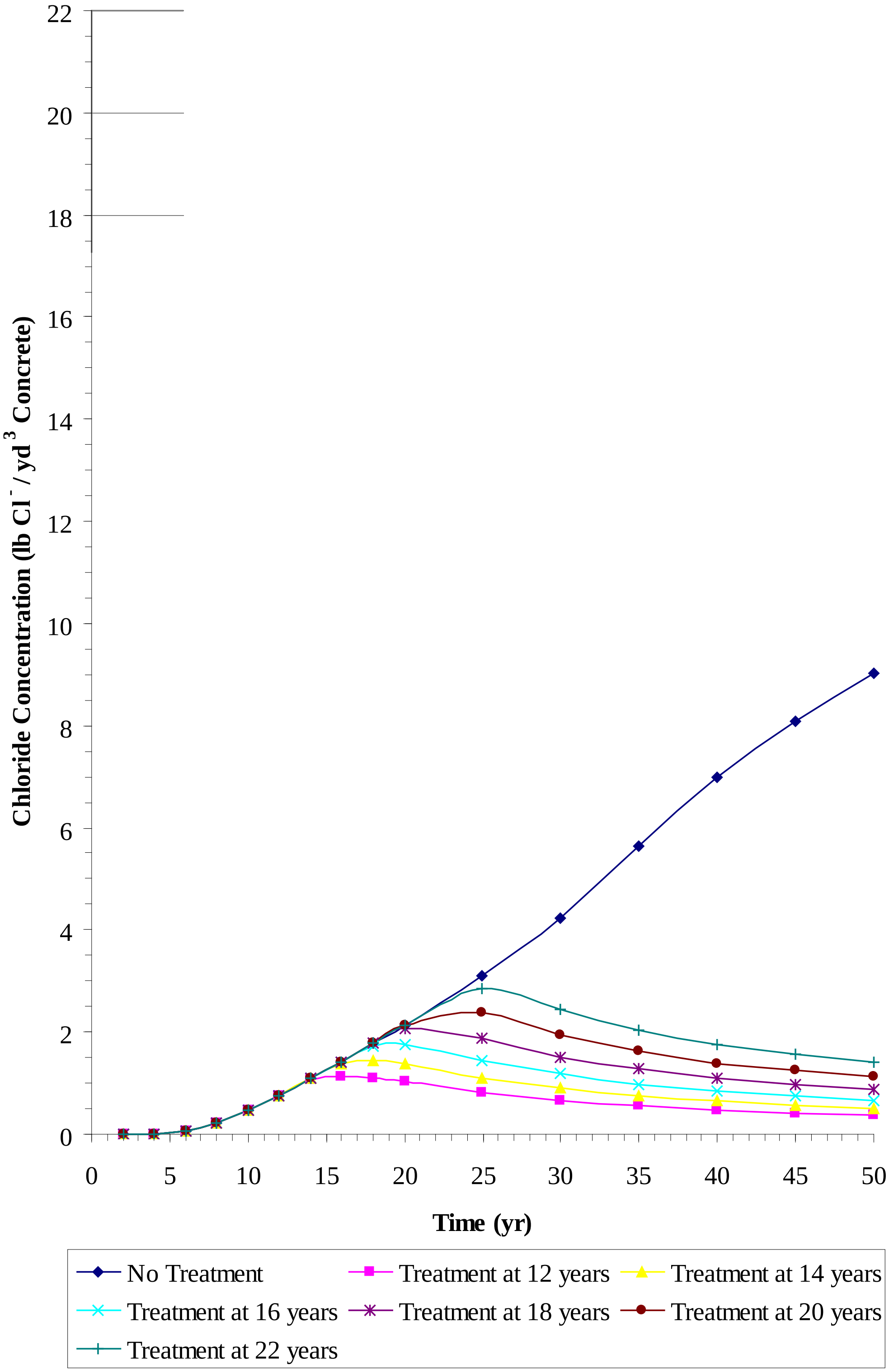

FIGURE B.13 Chloride concentrations of decks without SIPMFs with 3.0-in. OCD for 0.5-in. scarification and 1.5-in. overlay treatments.

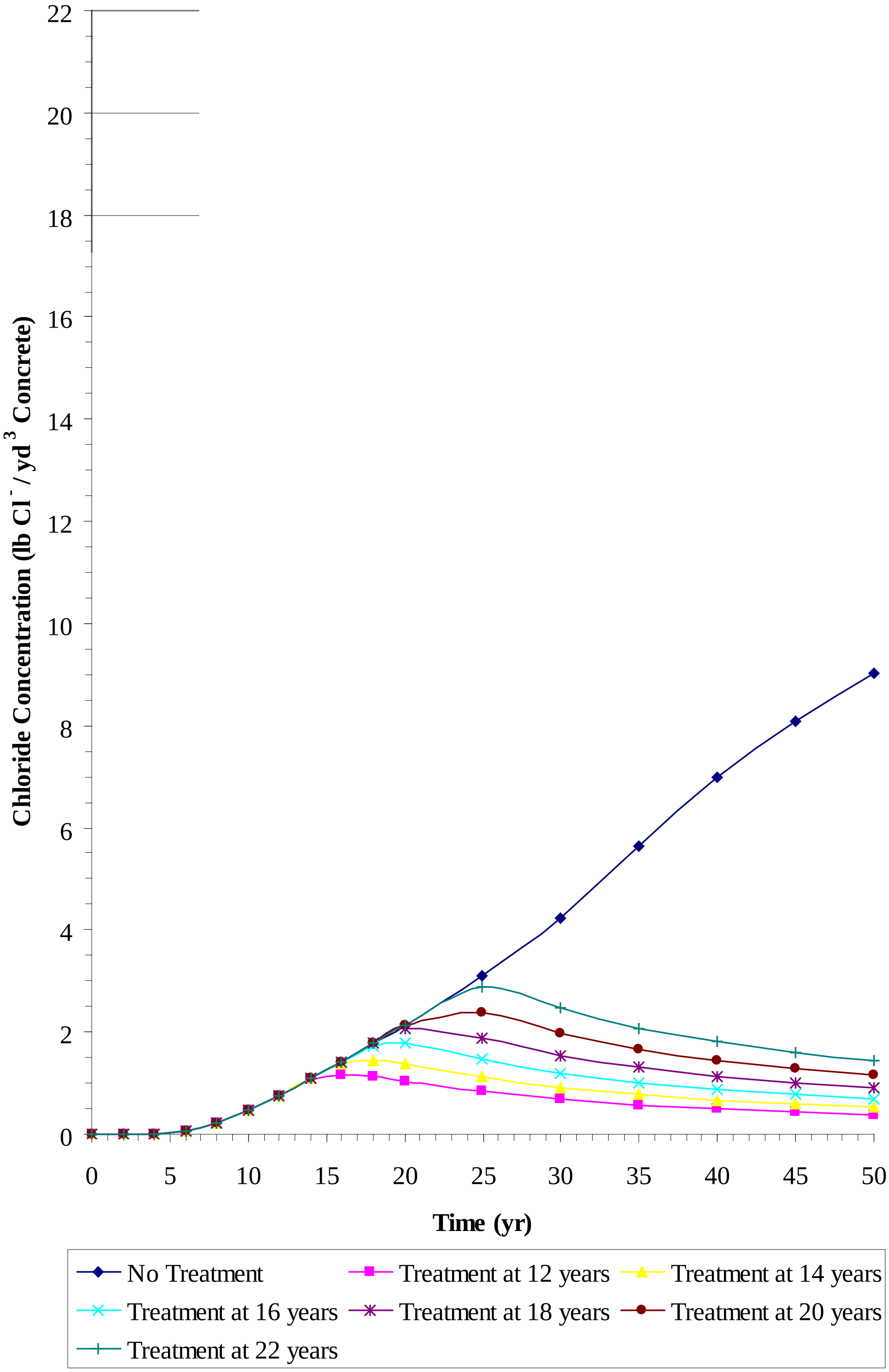

FIGURE B.14 Chloride concentrations of decks without SIPMFs with 3.0-in. OCD for 0.5-in. scarification and 2.0-in. overlay treatments.

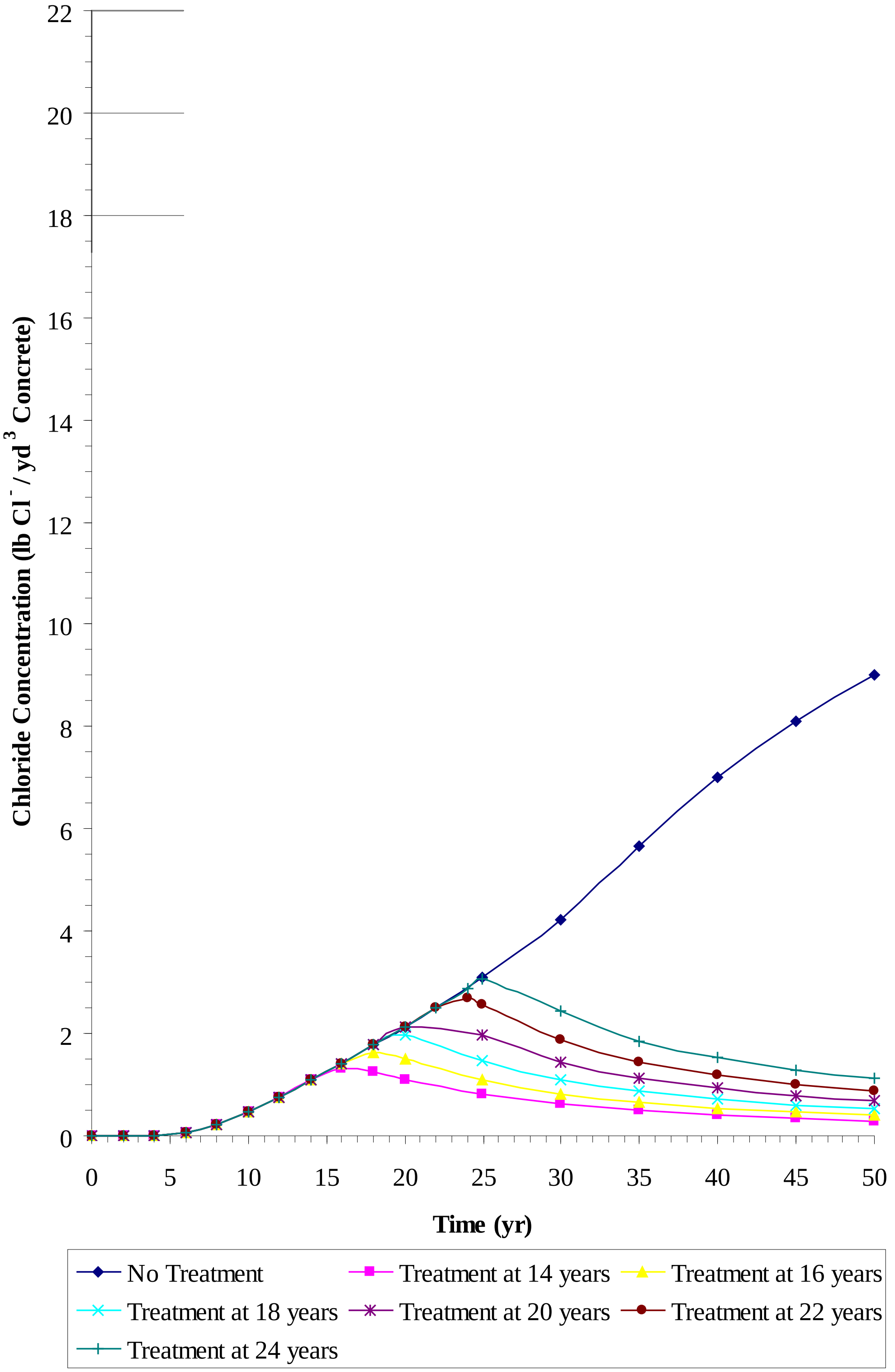

FIGURE B.15 Chloride concentrations of decks without SIPMFs with 3.0-in. OCD for 1.0-in. scarification and 1.5-in. overlay treatments.

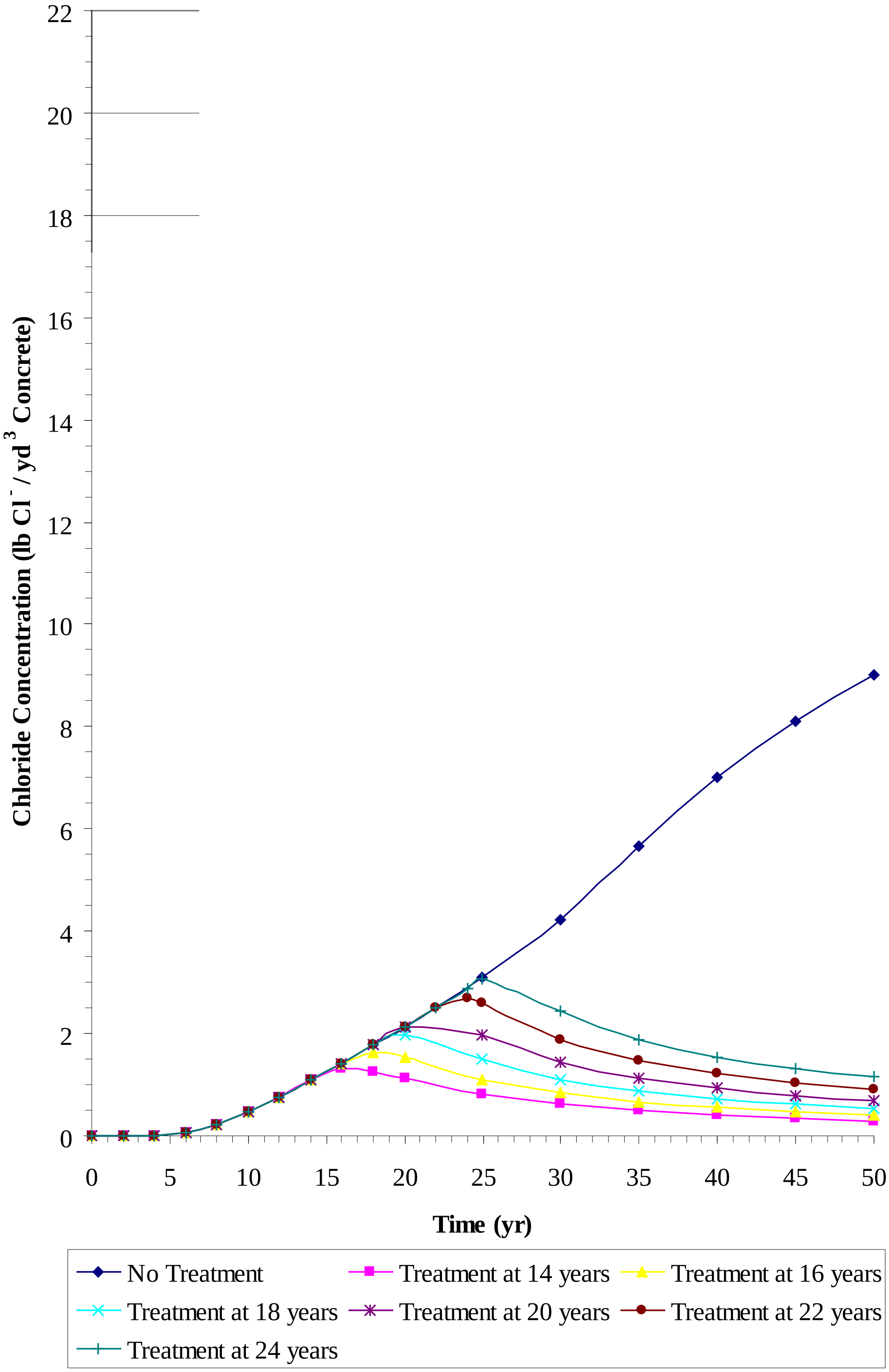

FIGURE B.16 Chloride concentrations of decks without SIPMFs with 3.0-in. OCD for 1.0-in. scarification and 2.0-in. overlay treatments.

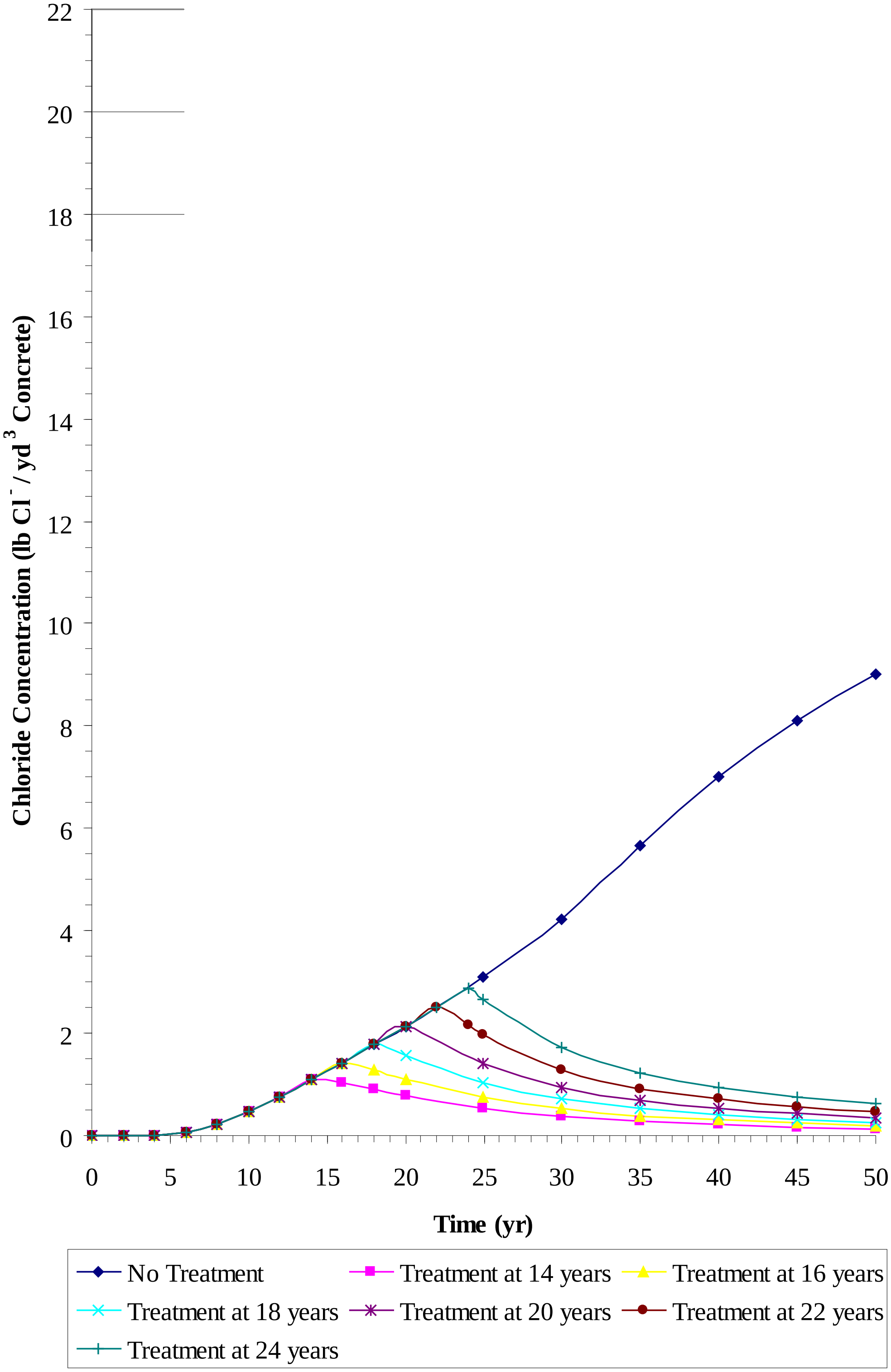

FIGURE B.17 Chloride concentrations of decks without SIPMFs with 3.0-in. OCD for 1.5-in. scarification and 1.5-in. overlay treatments.

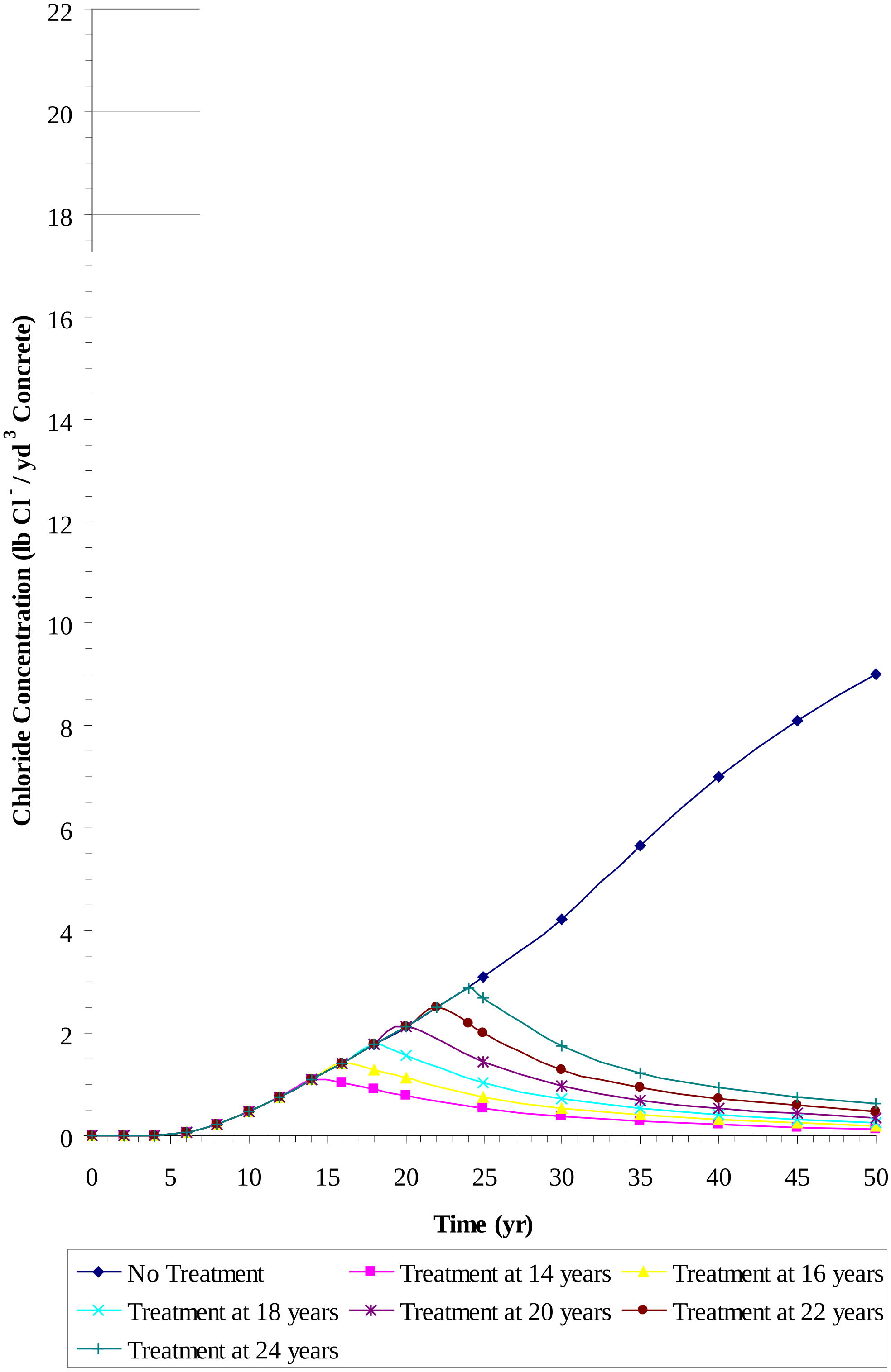

FIGURE B.18 Chloride concentrations of decks without SIPMFs with 3.0-in. OCD for 1.5-in. scarification and 2.0-in. overlay treatments.

APPENDIX C:

CHLORIDE CONCENTRATION PROFILES FOR DECKS WITH STAY-IN-PLACE METAL FORMS

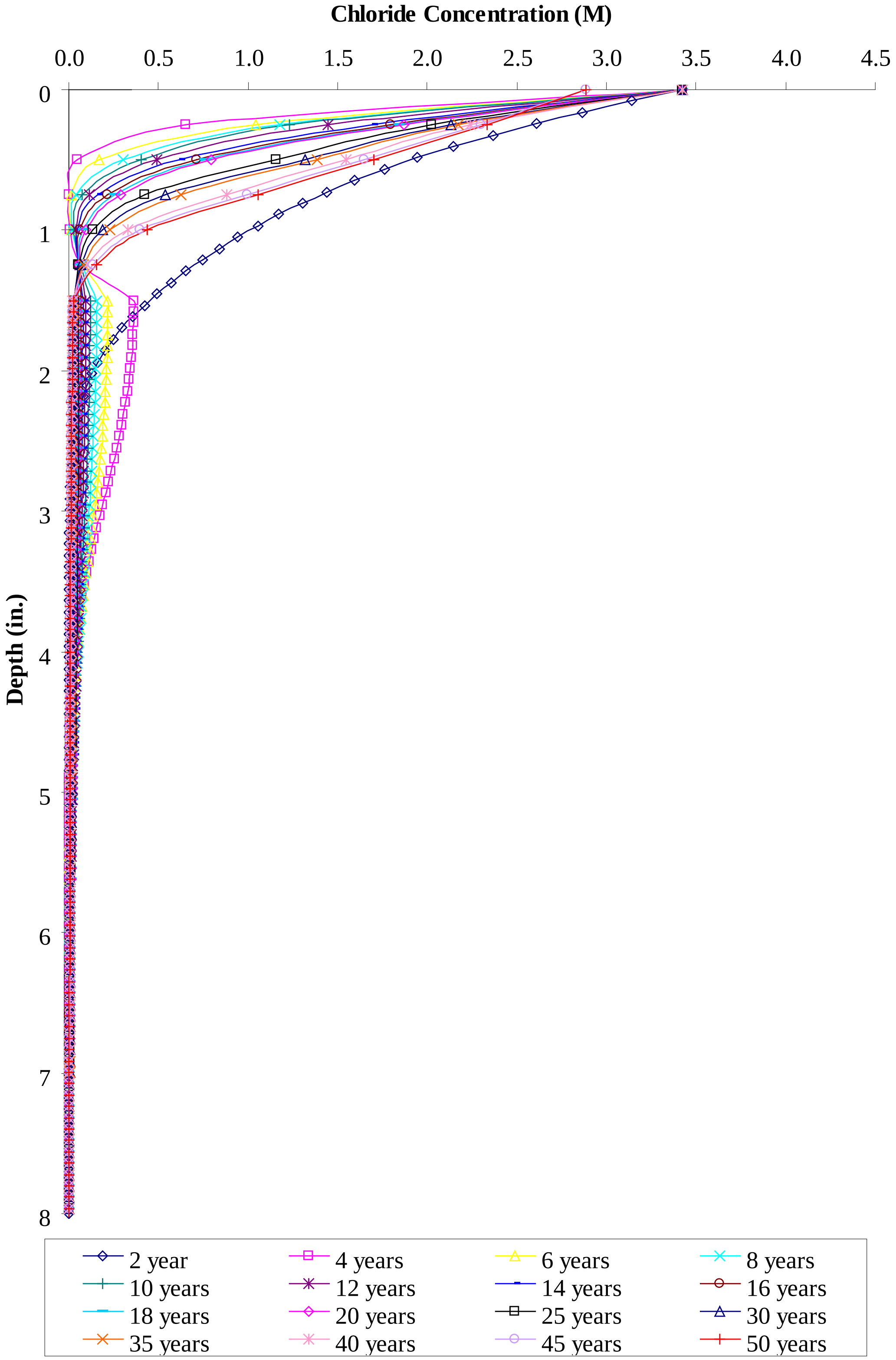

FIGURE C.1 Chloride concentrations of deck with SIPMFs with a 2.0-in. OCD and 0.5-in. scarification and 1.5-in. overlay treatment applied at 2 years.

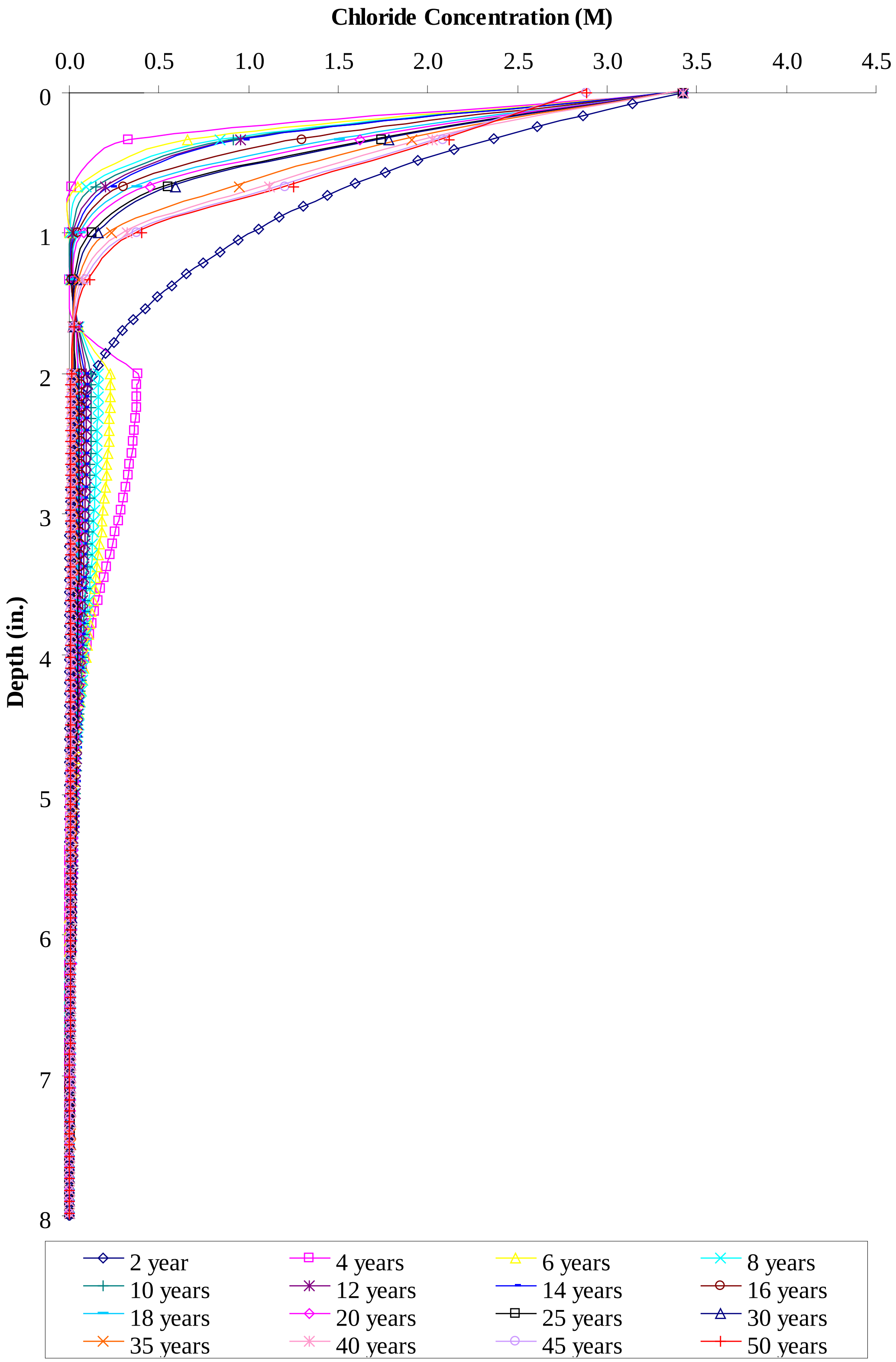

FIGURE C.2 Chloride concentrations of decks with SIPMFs with a 2.0-in. OCD and 0.5-in. scarification and 2.0-in. overlay treatment applied at 2 years.

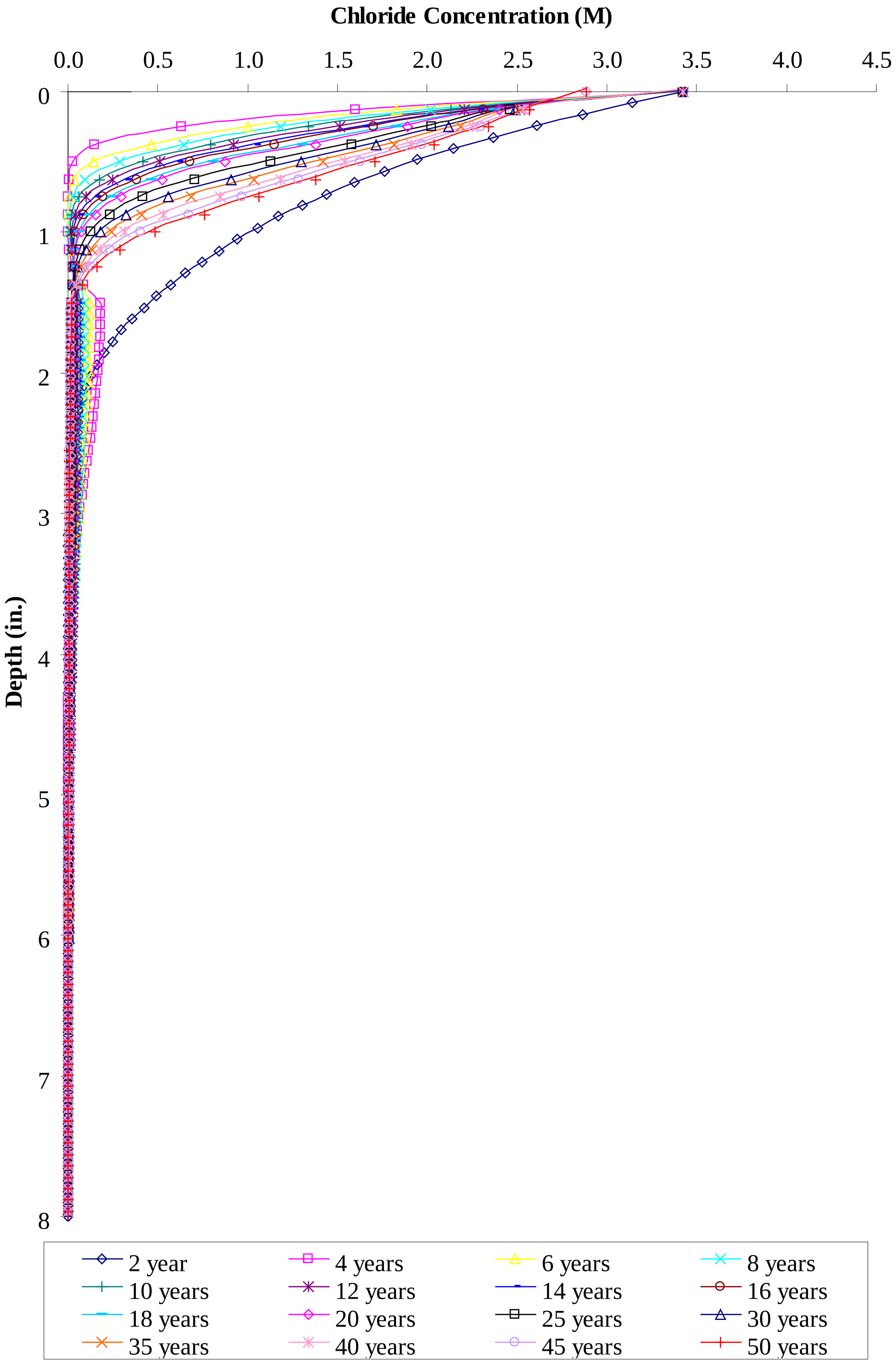

FIGURE C.3 **Chloride concentrations of decks with SIPMFs with a 2.0-in. OCD and 1.0-in. scarification and 1.5-in. overlay treatment applied at 2 years.**

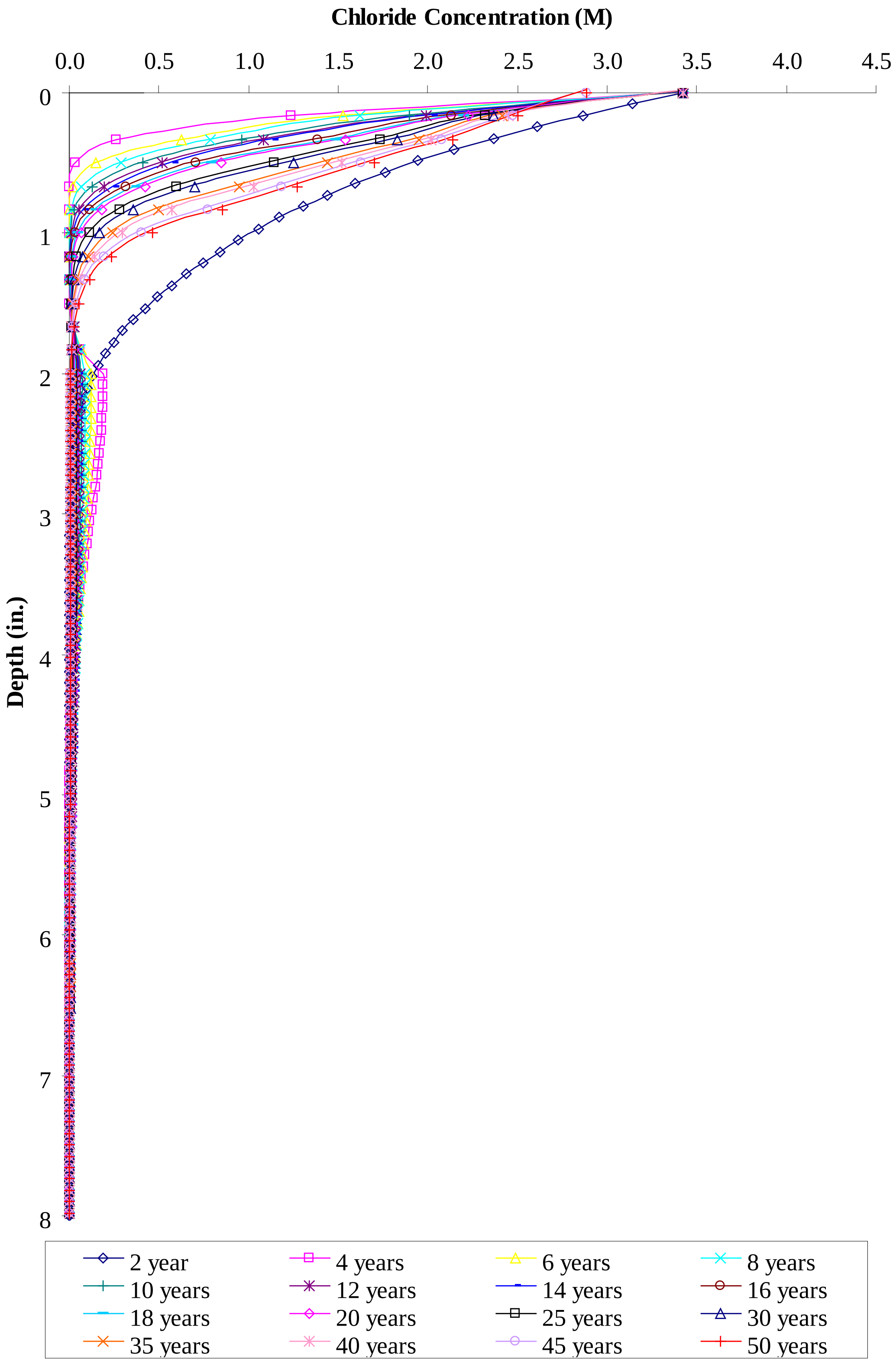

FIGURE C.4 Chloride concentrations of decks with SIPMFs with a 2.0-in. OCD and 1.0-in. scarification and 2.0-in. overlay treatment applied at 2 years.

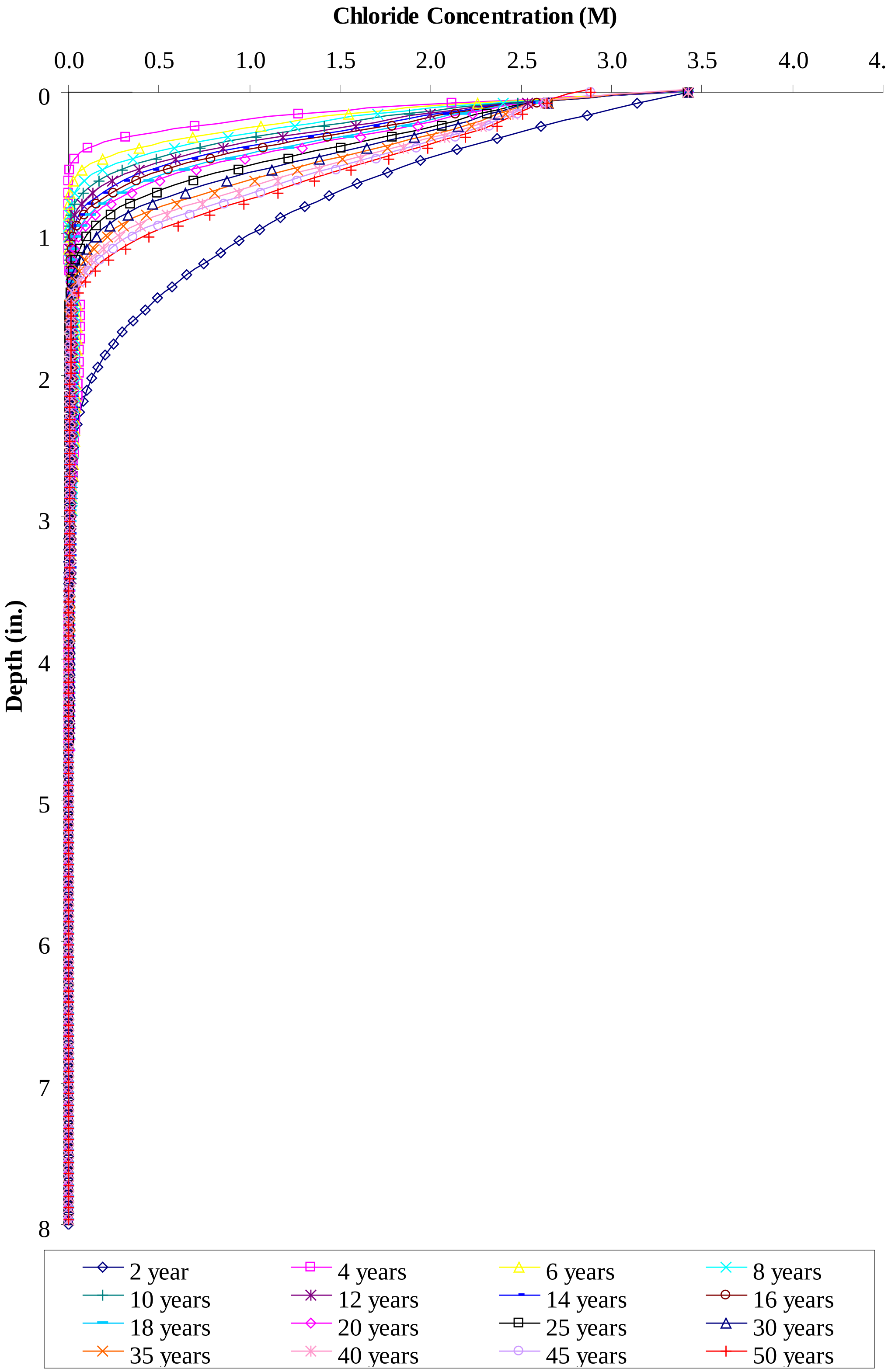

FIGURE C.5 Chloride concentrations of decks with SIPMFs with a 2.0-in. OCD and 1.5-in. scarification and 1.5-in. overlay treatment applied at 2 years.

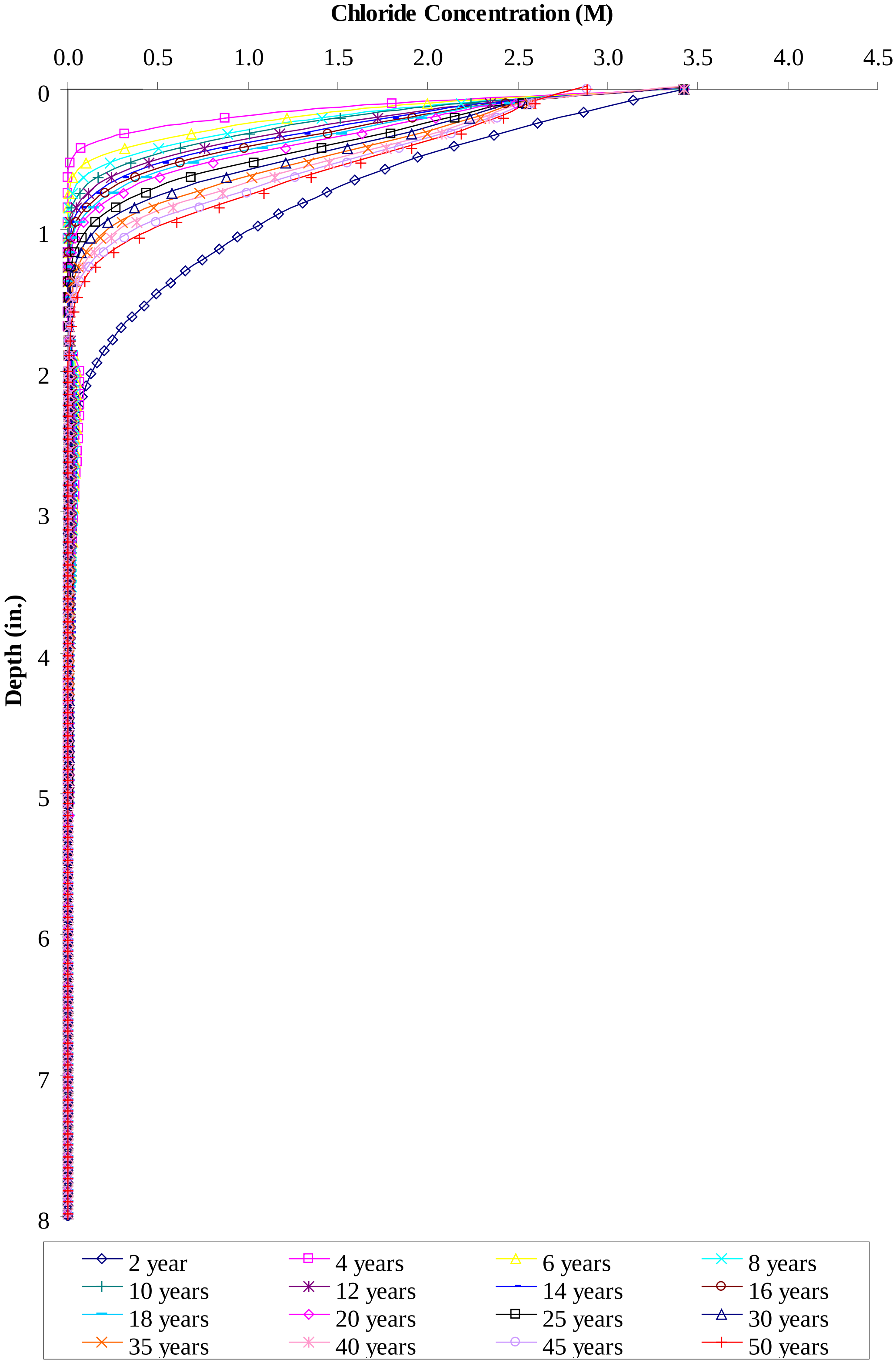

FIGURE C.6 Chloride concentrations of decks with SIPMFs with a 2.0-in. OCD and 1.5-in. scarification and 2.0-in. overlay treatment applied at 2 years.

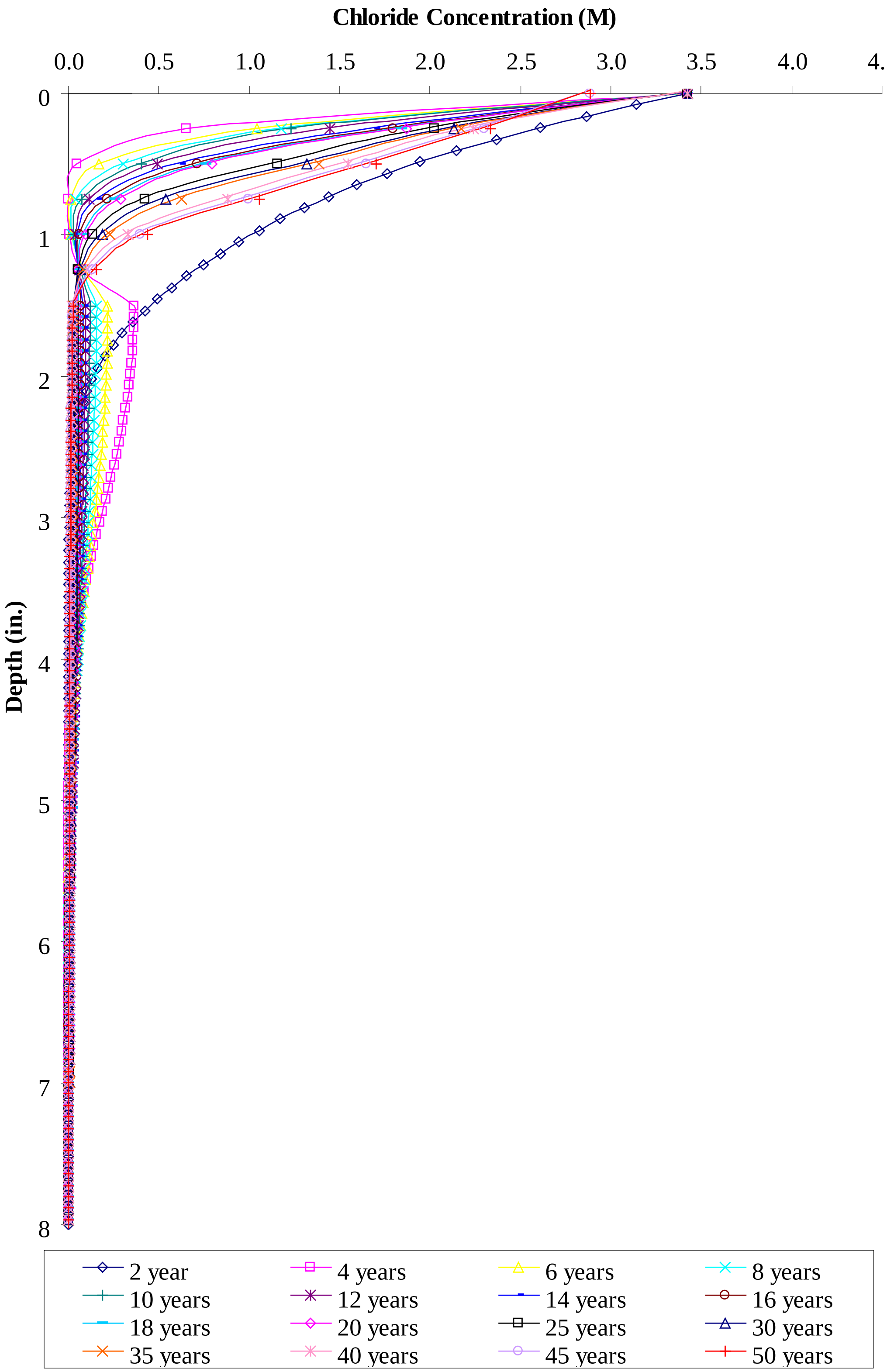

FIGURE C.7 Chloride concentrations of decks with SIPMFs with a 2.5-in. OCD and 0.5-in. scarification and 1.5-in. overlay treatment applied at 2 years.

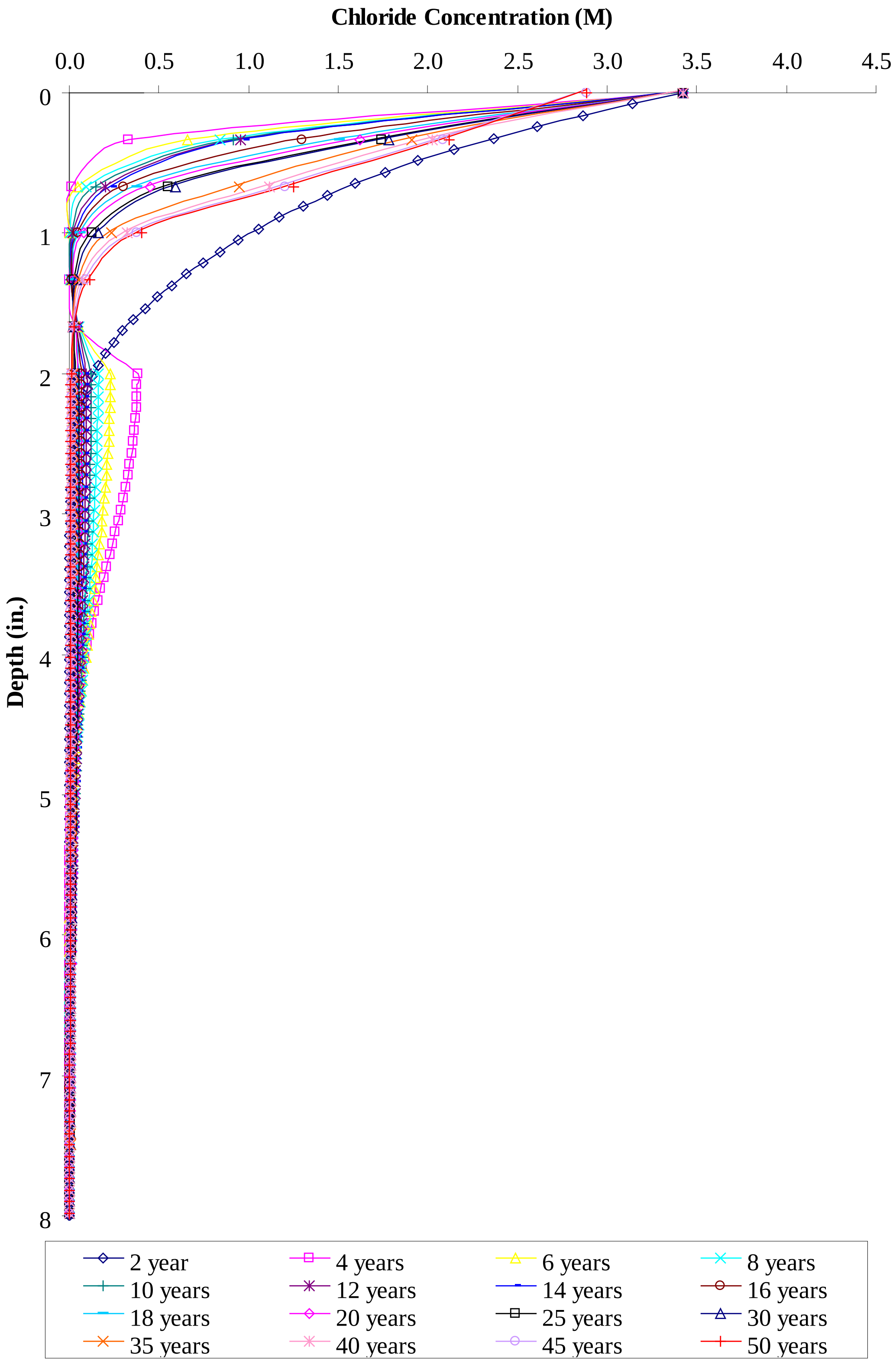

FIGURE C.8 Chloride concentrations of decks with SIPMFs with a 2.5-in. OCD and 0.5-in. scarification and 2.0-in. overlay treatment applied at 2 years.

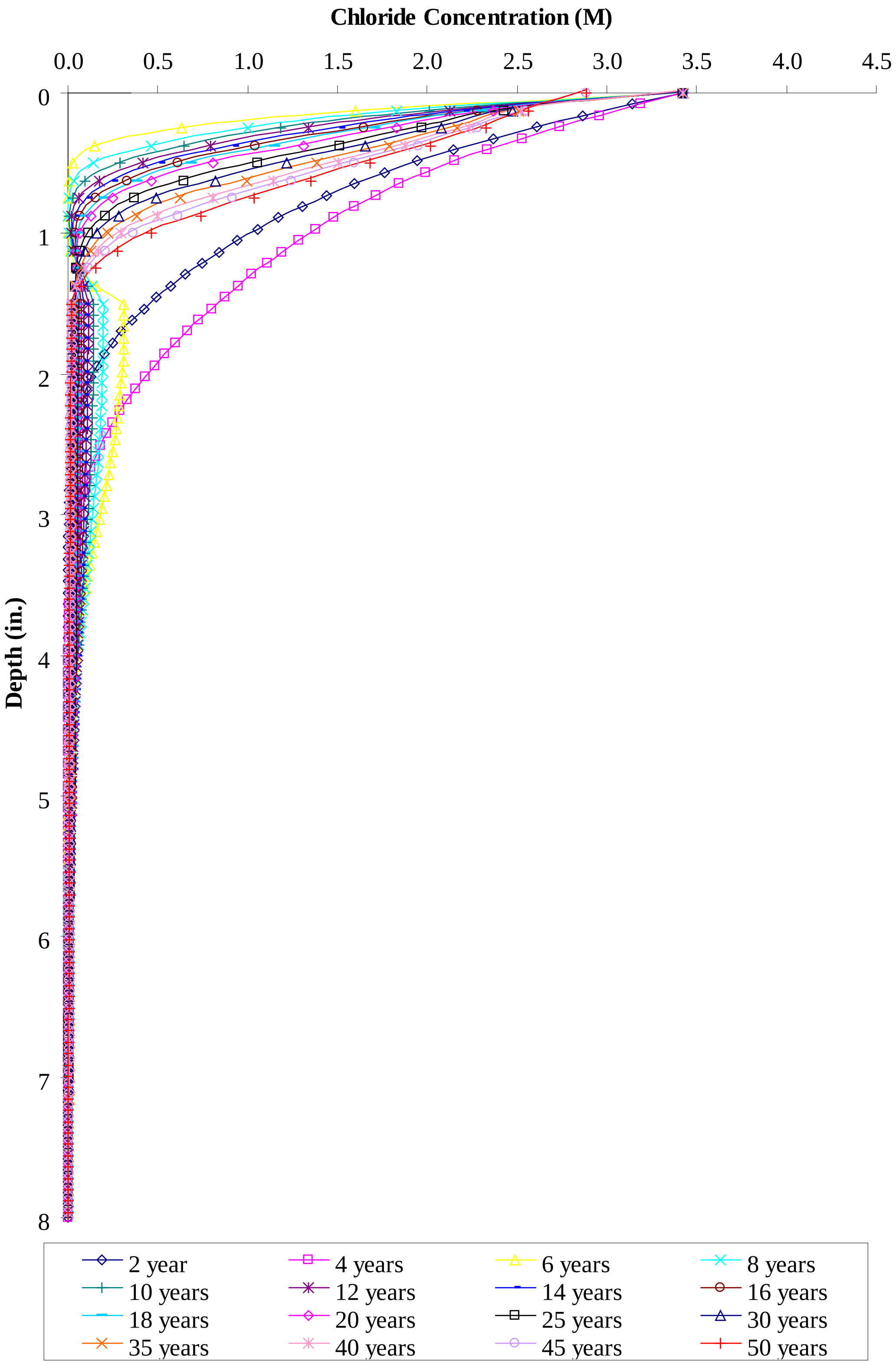

FIGURE C.9 Chloride concentrations of decks with SIPMFs with a 2.5-in. OCD and 1.0-in. scarification and 1.5-in. overlay treatment applied at 4 years.

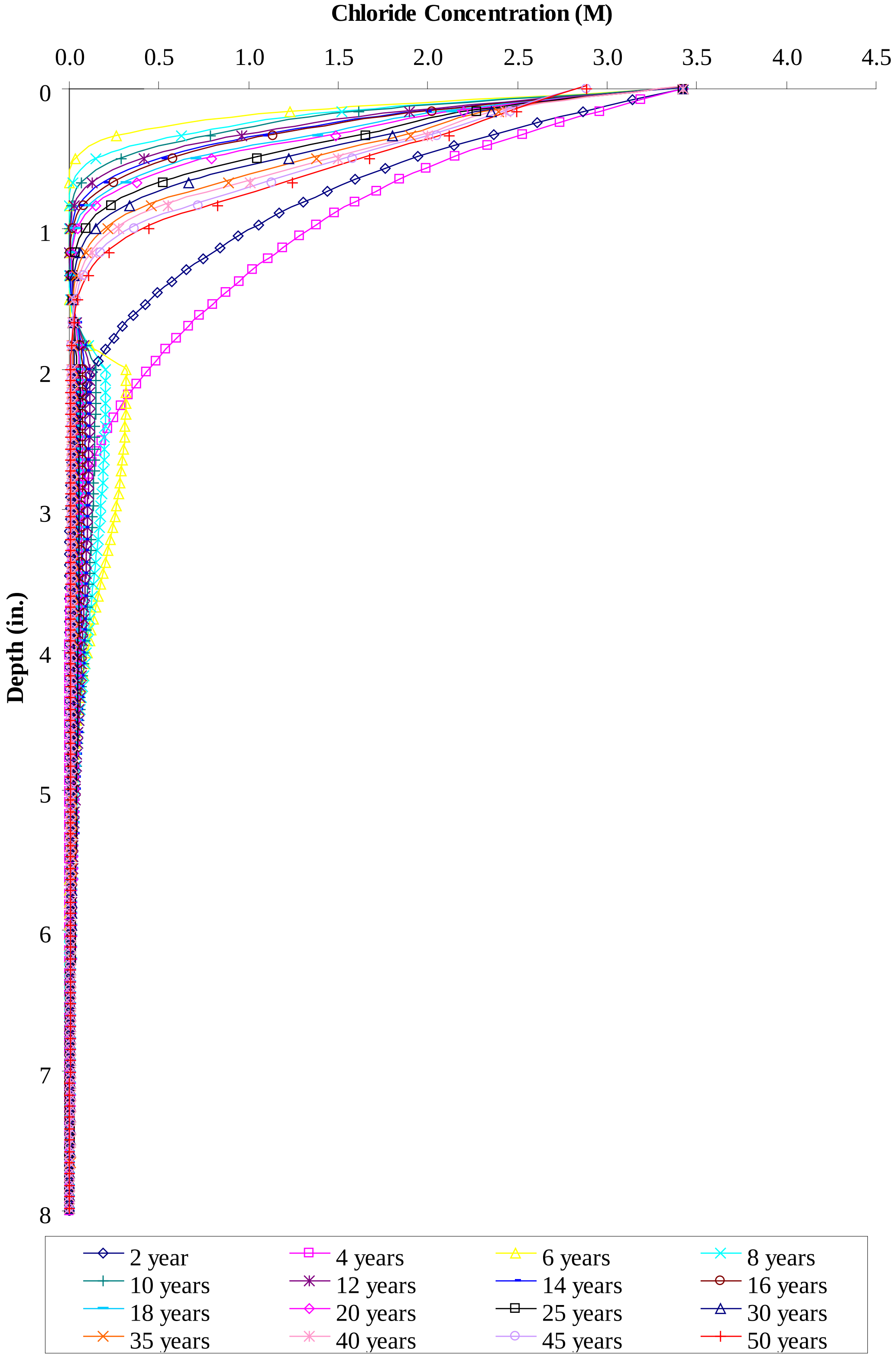

FIGURE C.10 Chloride concentrations of decks with SIPMFs with a 2.5-in. OCD and 1.0-in. scarification and 2.0-in. overlay treatment applied at 4 years.

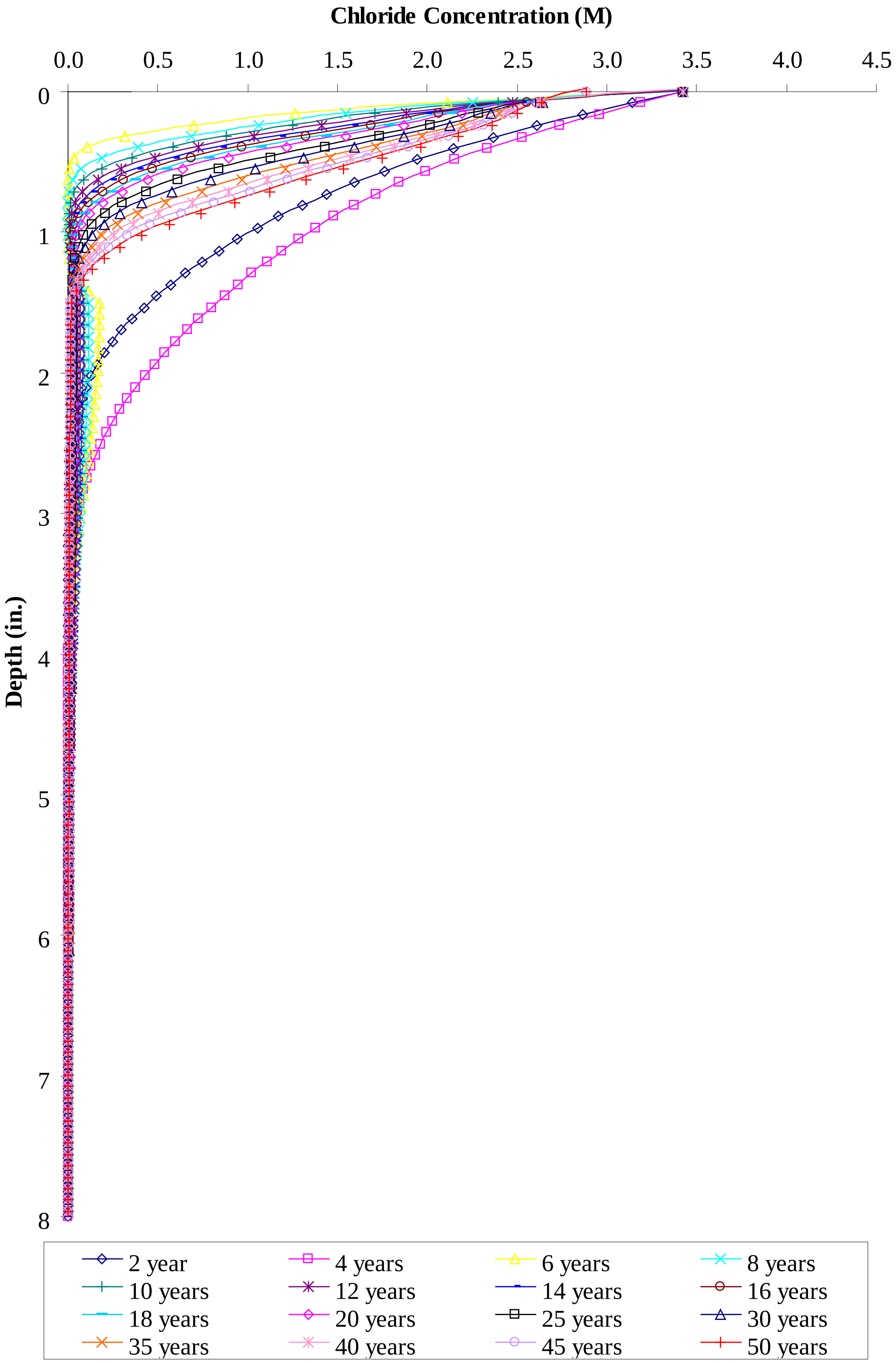

FIGURE C.11 Chloride concentrations of decks with SIPMFs with a 2.5-in. OCD and 1.5-in. scarification and 1.5-in. overlay treatment applied at 4 years.

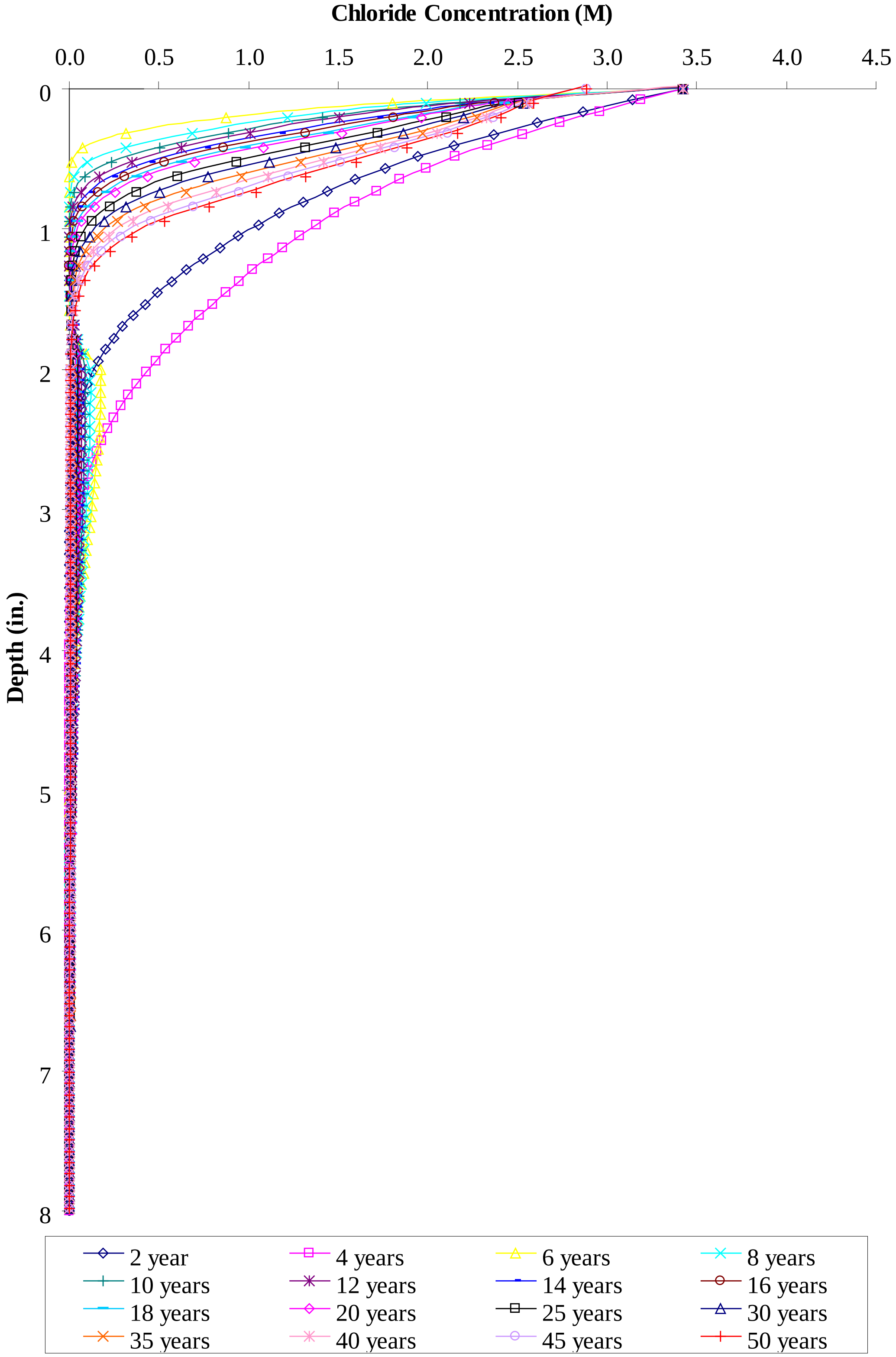

FIGURE C.12 Chloride concentrations of decks with SIPMFs with a 2.5-in. OCD and 1.5-in. scarification and 2.0-in. overlay treatment applied at 4 years.

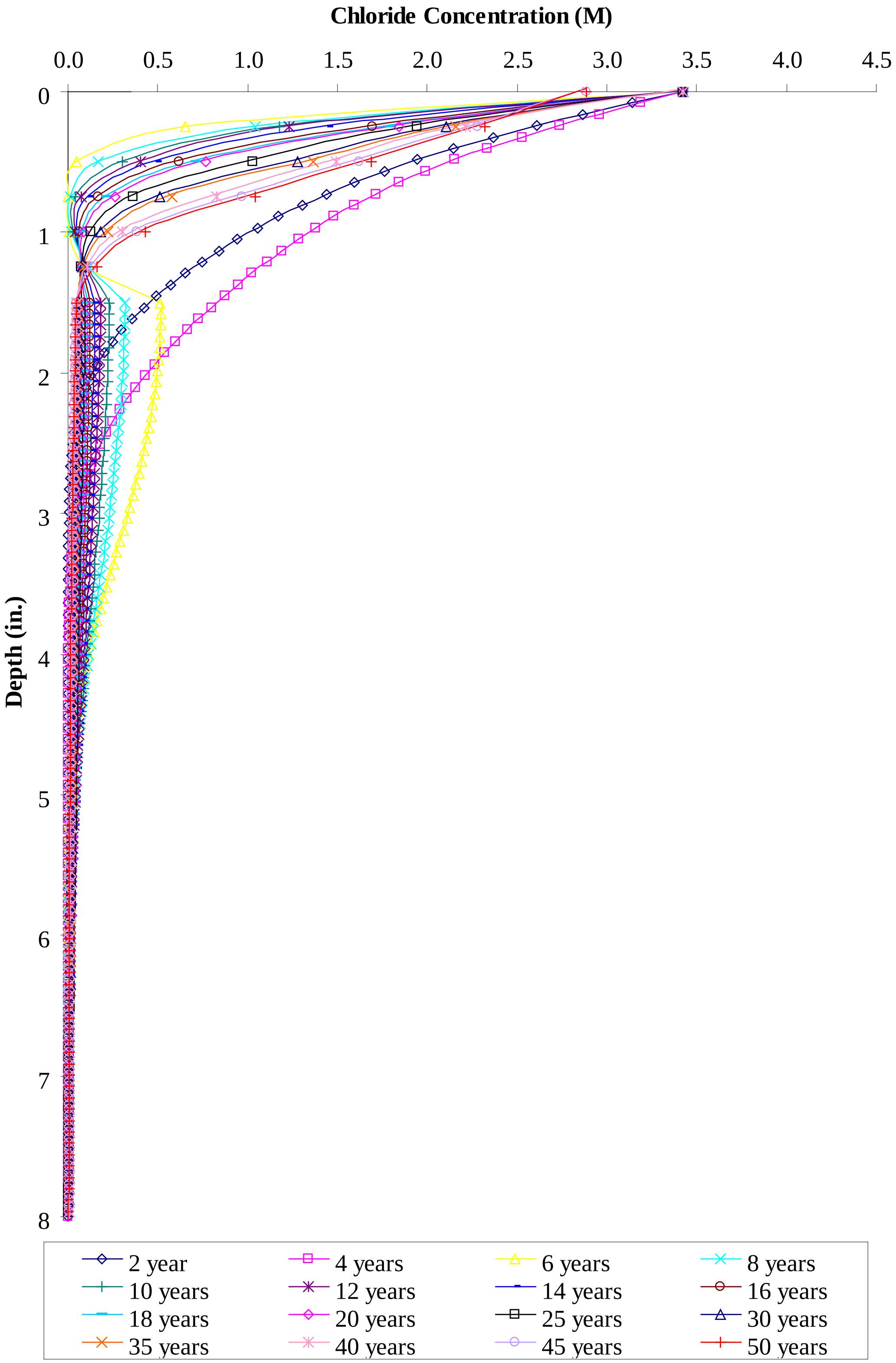

FIGURE C.13 Chloride concentrations of decks with SIPMFs with a 3.0-in. OCD and 0.5-in. scarification and 1.5-in. overlay treatment applied at 4 years.

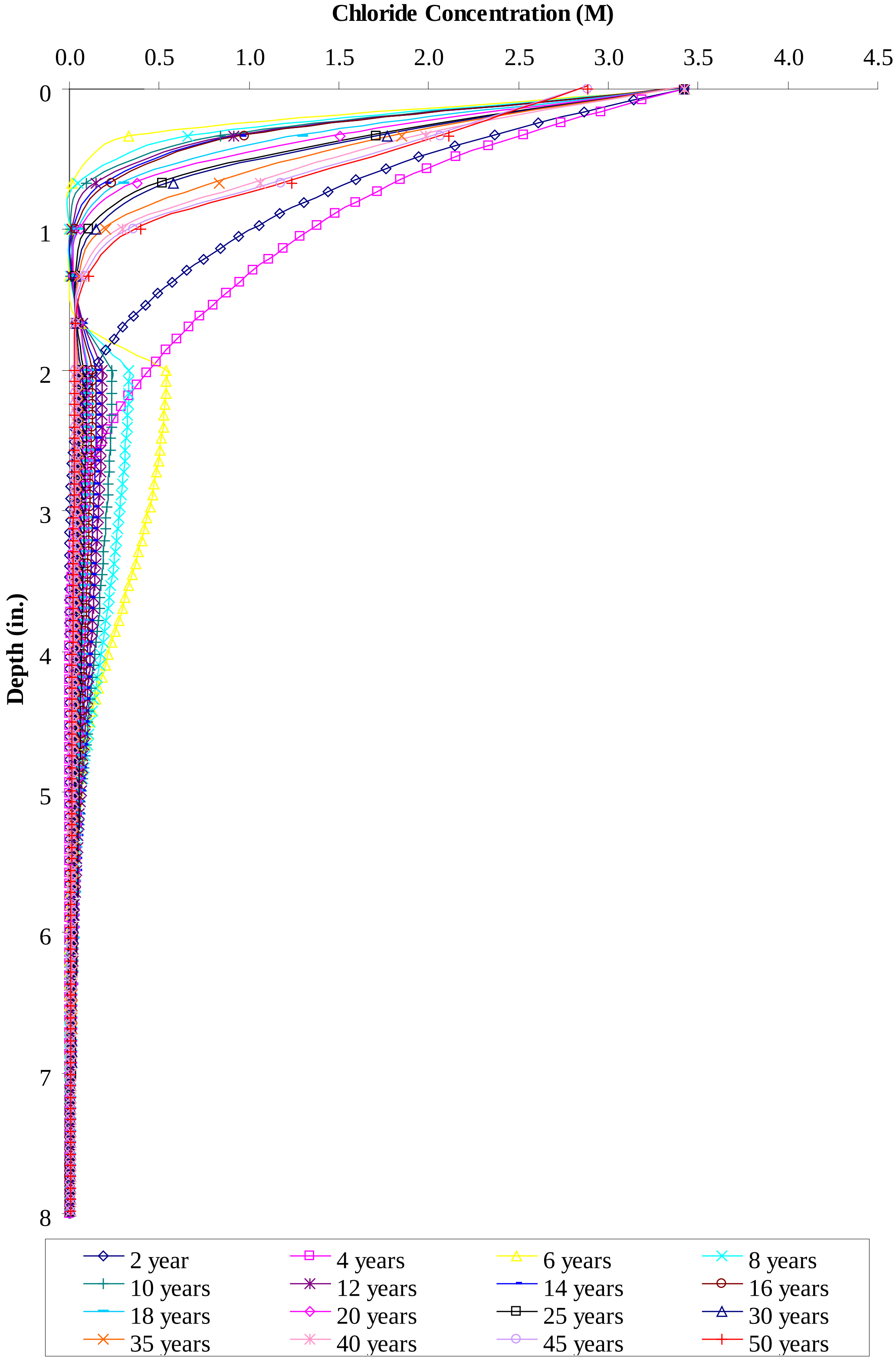

FIGURE C.14 Chloride concentrations of decks with SIPMFs with a 3.0-in. OCD and 0.5-in. scarification and 2.0-in. overlay treatment applied at 4 years.

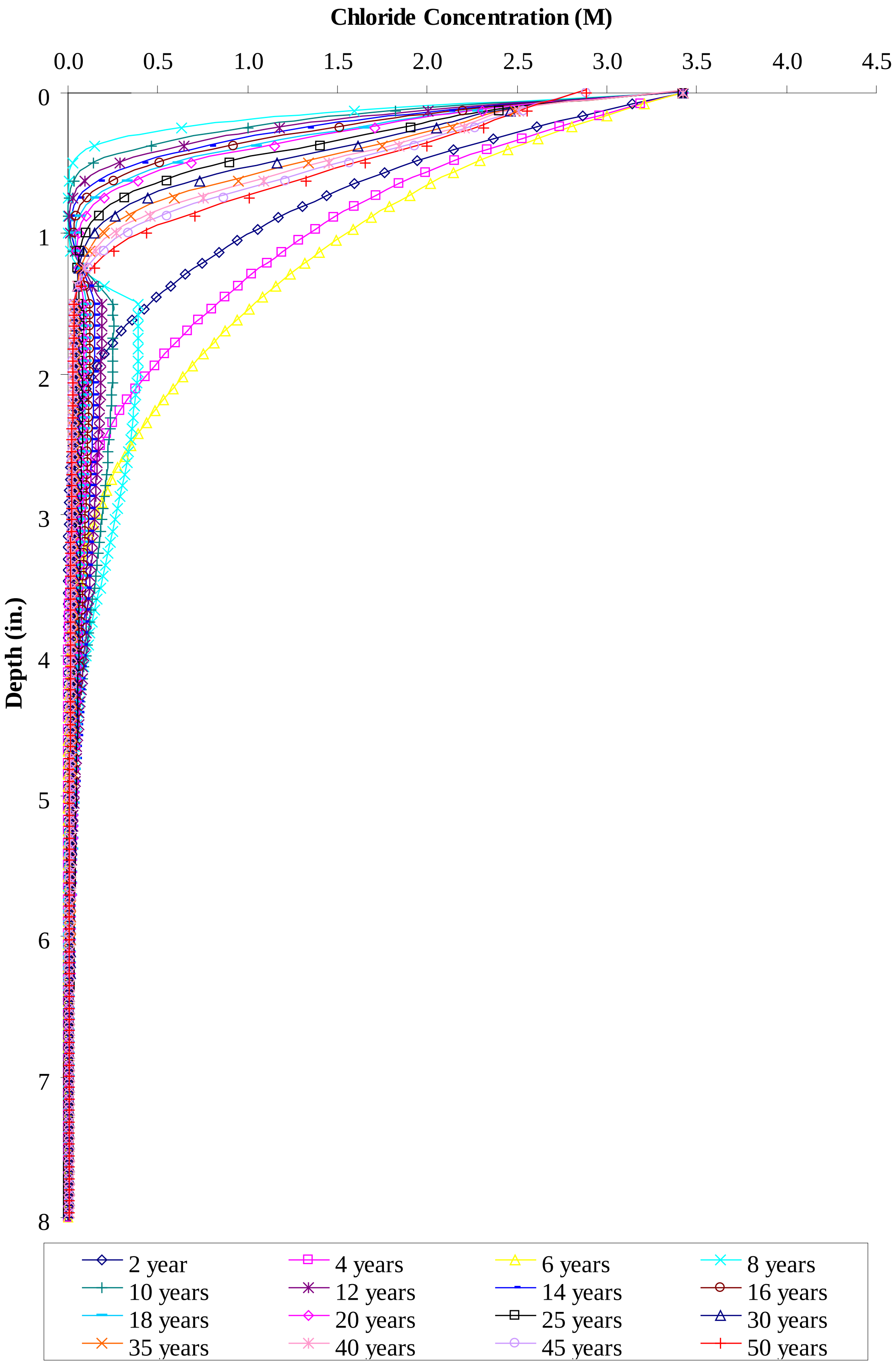

FIGURE C.15 Chloride concentrations of decks with SIPMFs with a 3.0-in. OCD and 1.0-in. scarification and 1.5-in. overlay treatment applied at 6 years.

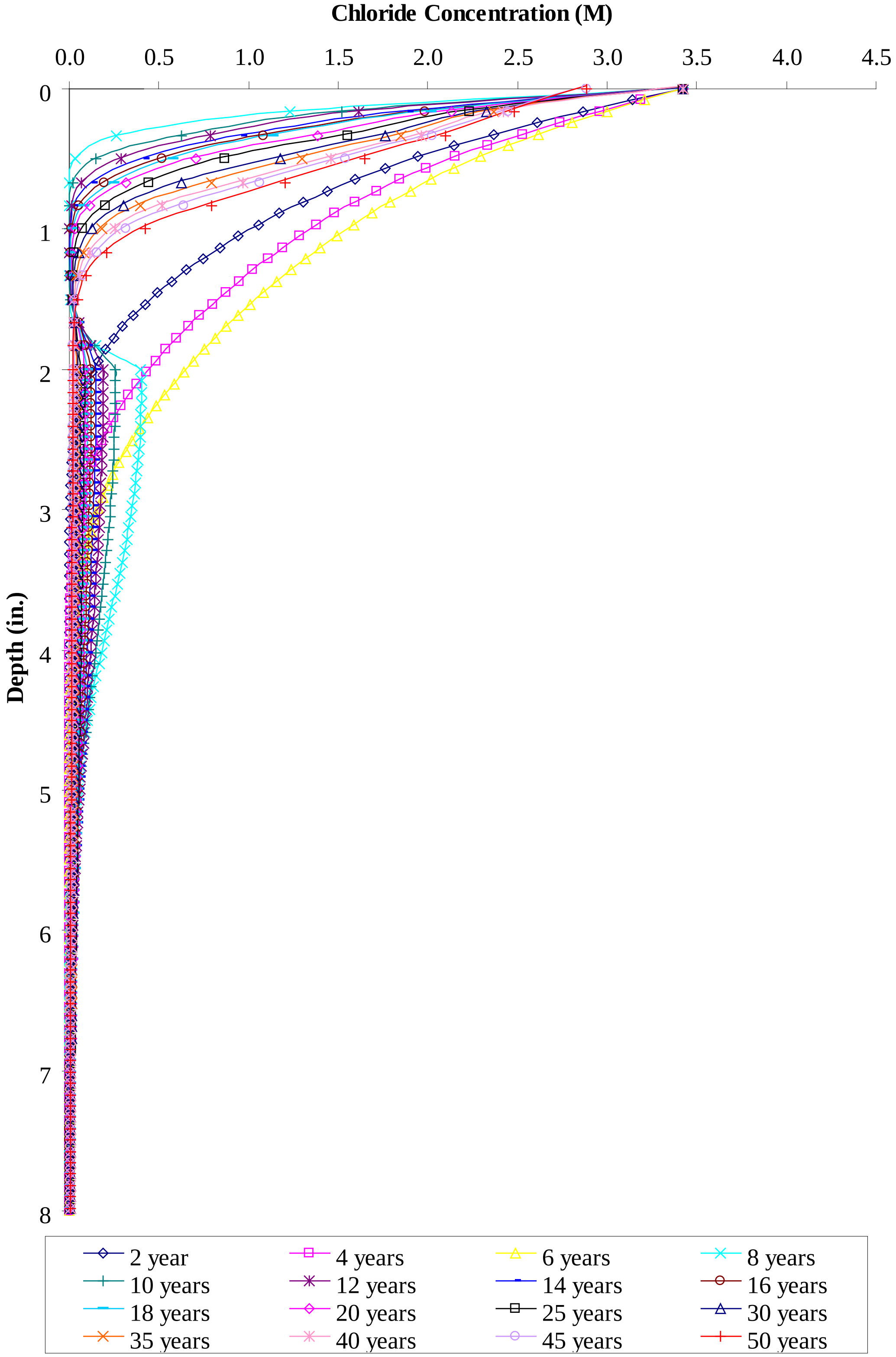

FIGURE C.16 Chloride concentrations of decks with SIPMFs with a 3.0-in. OCD and 1.0-in. scarification and 2.0-in. overlay treatment applied at 6 years.

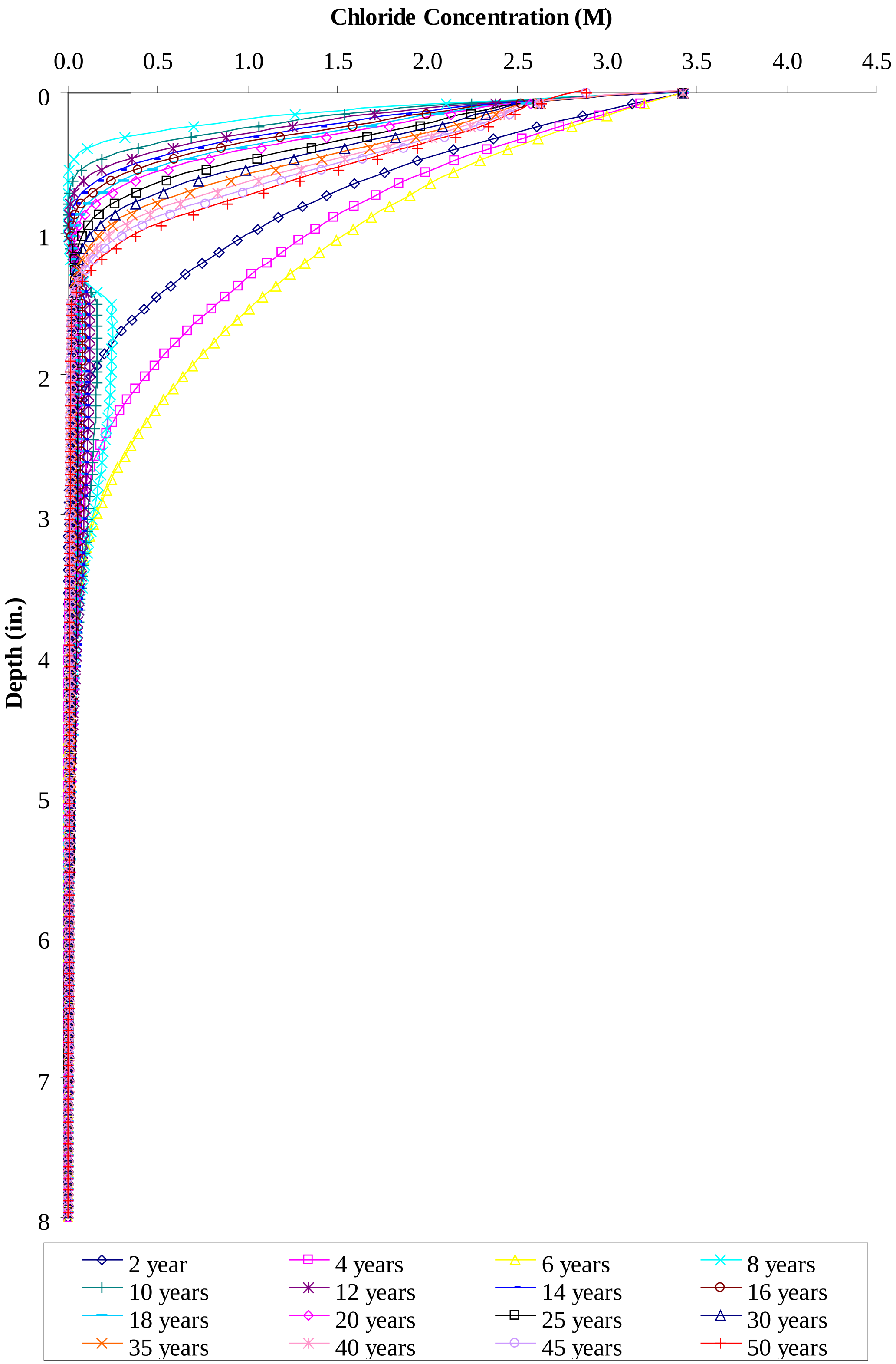

FIGURE C.17 Chloride concentrations of decks with SIPMFs with a 3.0-in. OCD and 1.5-in. scarification and 1.5-in. overlay treatment applied at 6 years.

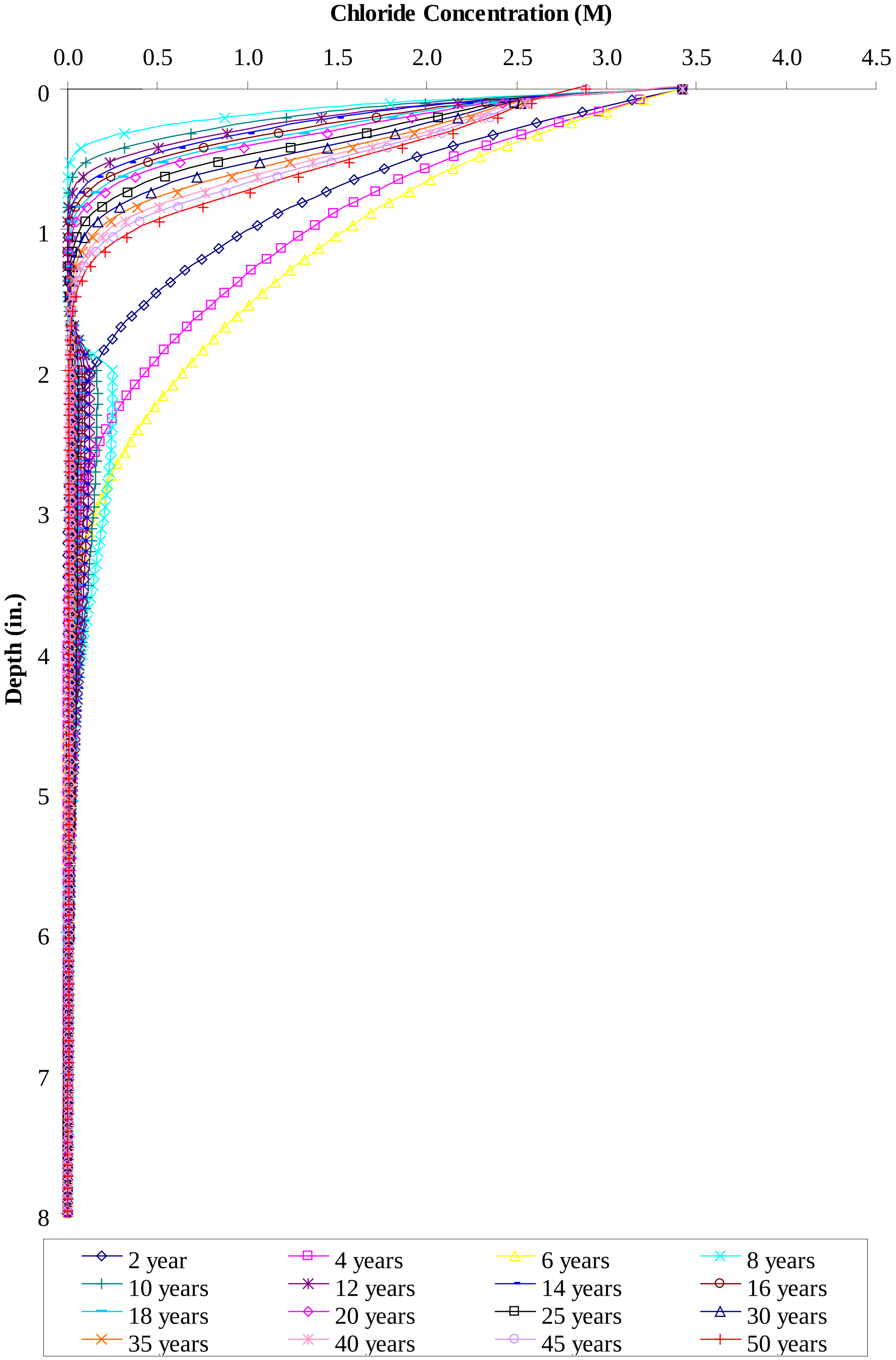

FIGURE C.18 Chloride concentrations of decks with SIPMFs with a 3.0-in. OCD and 1.5-in. scarification and 2.0-in. overlay treatment applied at 6 years.

APPENDIX D:

CHLORIDE CONCENTRATION PROFILES FOR DECKS WITHOUT STAY-IN-PLACE METAL FORMS

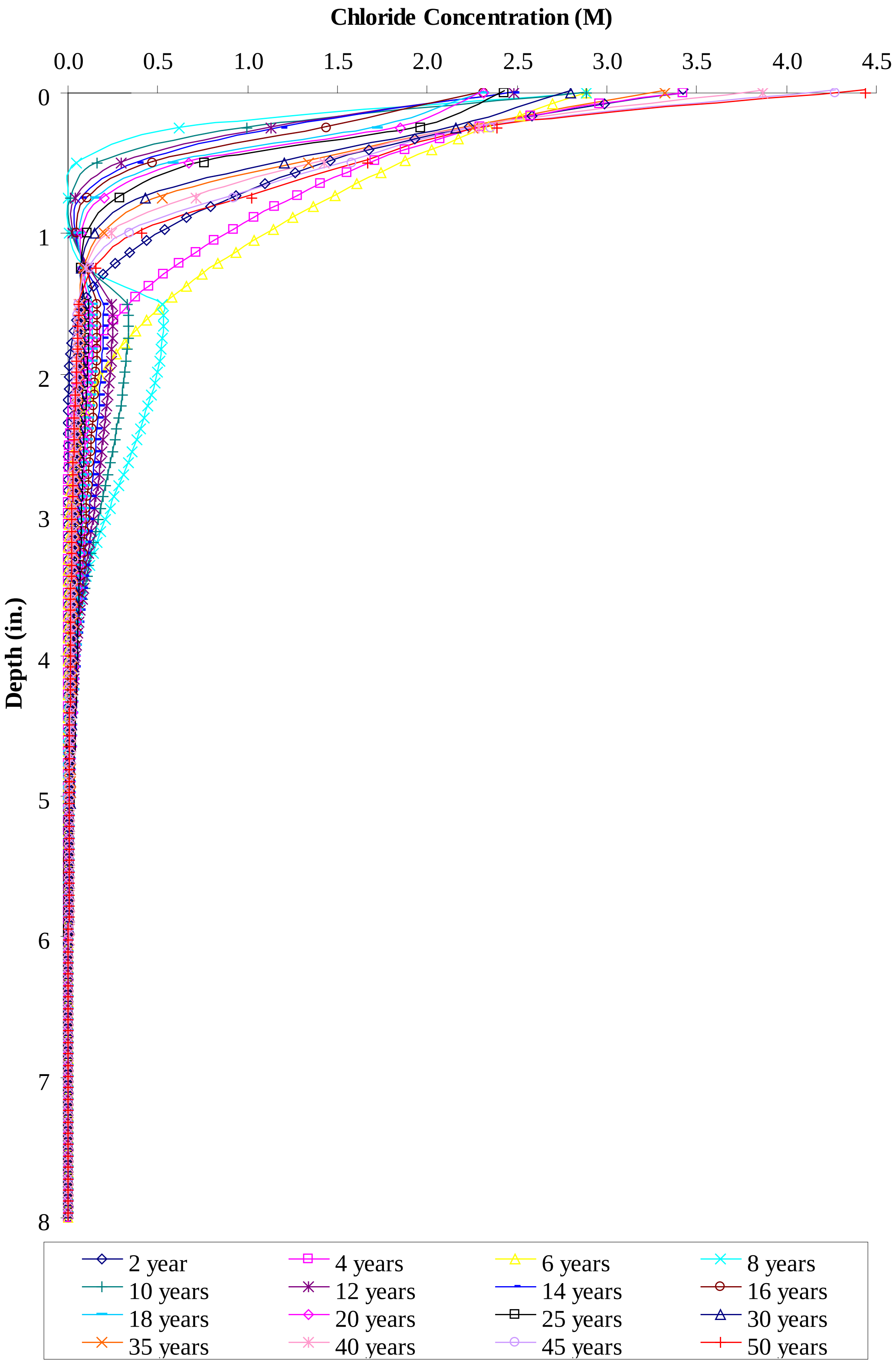

FIGURE D.1 Chloride concentrations of decks without SIPMFs with a 2.0-in. OCD and 0.5-in. scarification and 1.5-in. overlay treatment applied at 6 years.

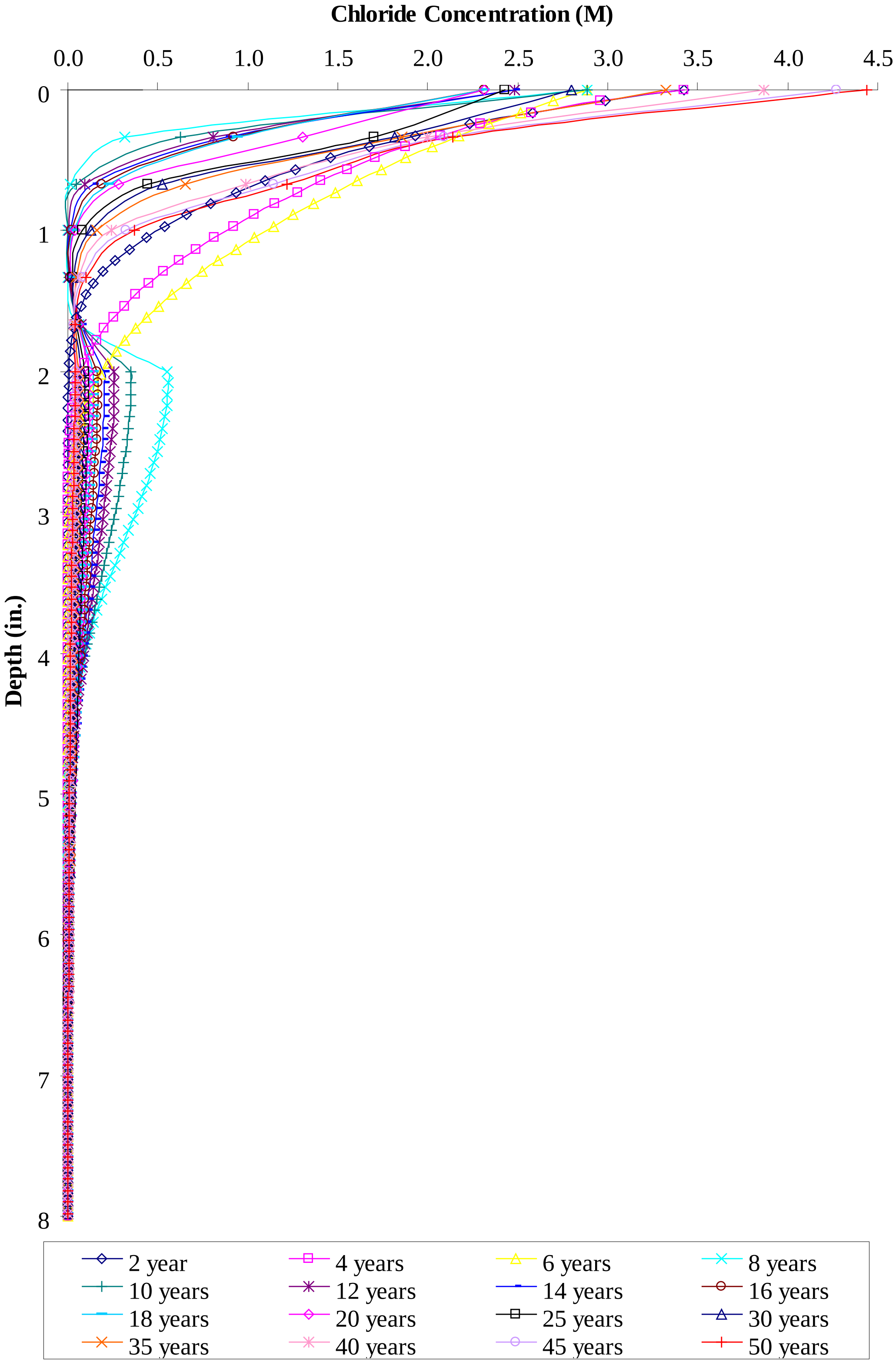

FIGURE D.2 Chloride concentrations of decks without SIPMFs with a 2.0-in. OCD and 0.5-in. scarification and 2.0-in. overlay treatment applied at 6 years.

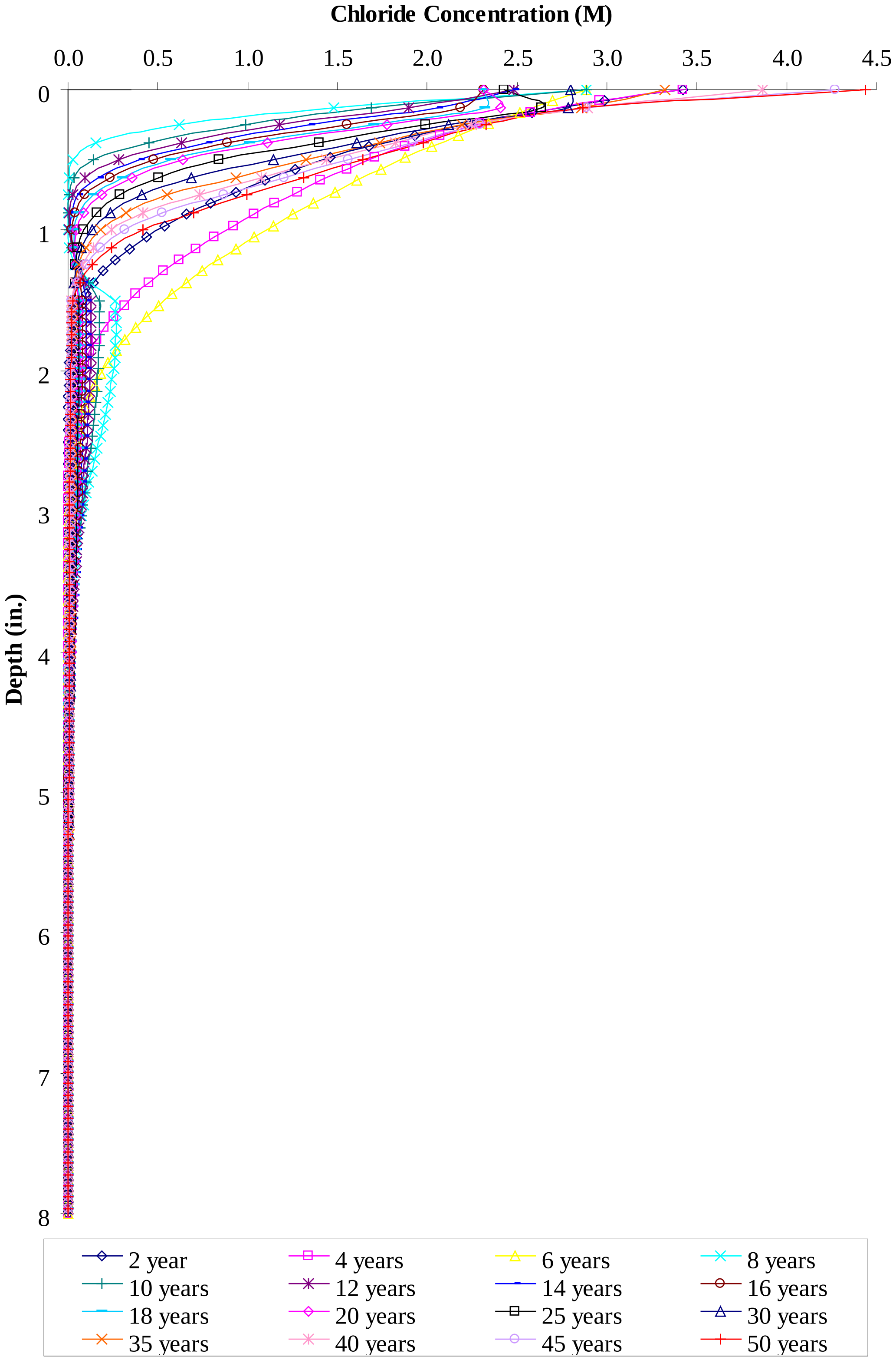

FIGURE D.3 Chloride concentrations of decks without SIPMFs with a 2.0-in. OCD and 1.0-in. scarification and 1.5-in. overlay treatment applied at 6 years.

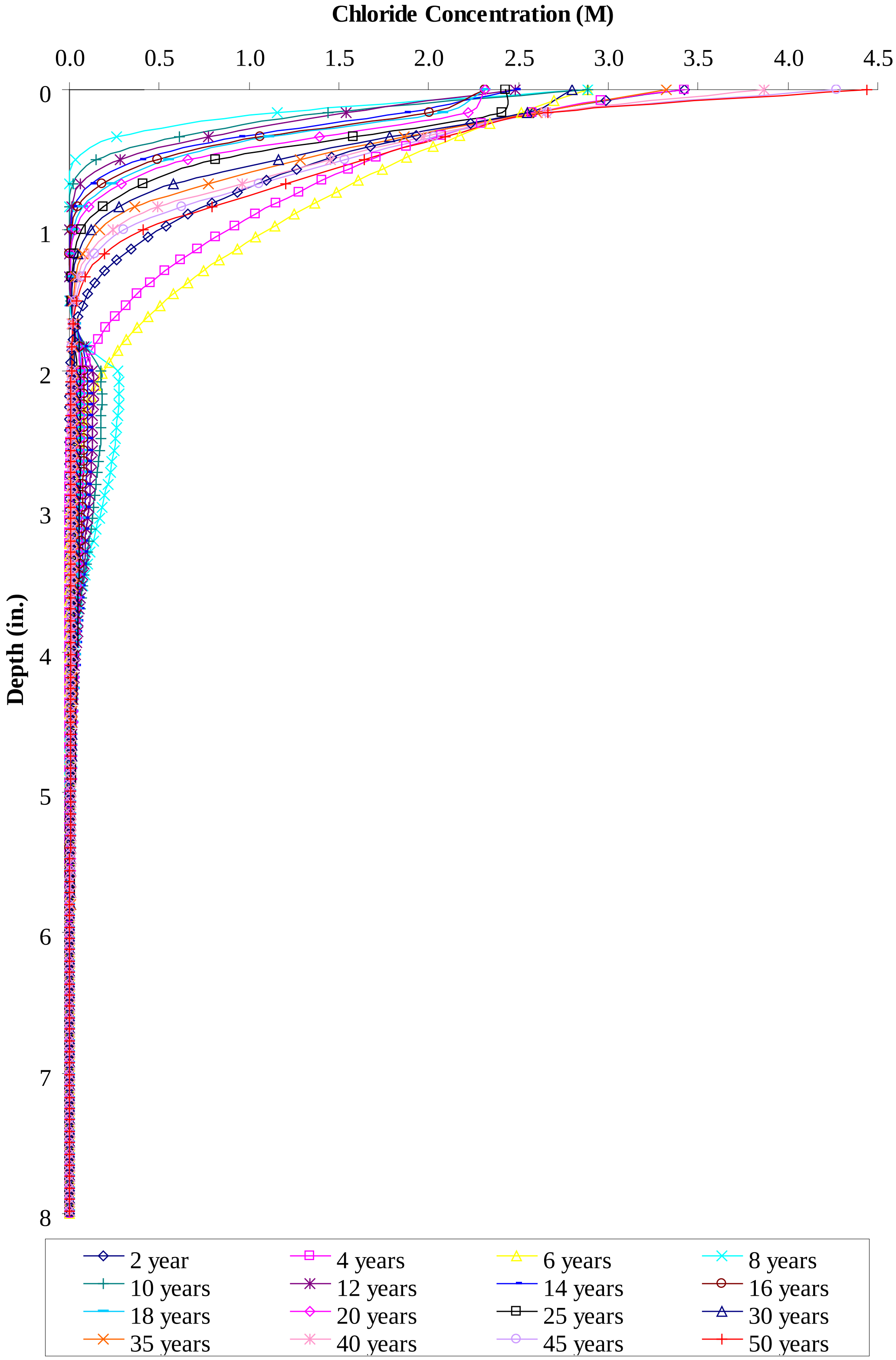

FIGURE D.4 Chloride concentrations of decks without SIPMFs with a 2.0-in. OCD and 1.0-in. scarification and 2.0-in. overlay treatment applied at 6 years.

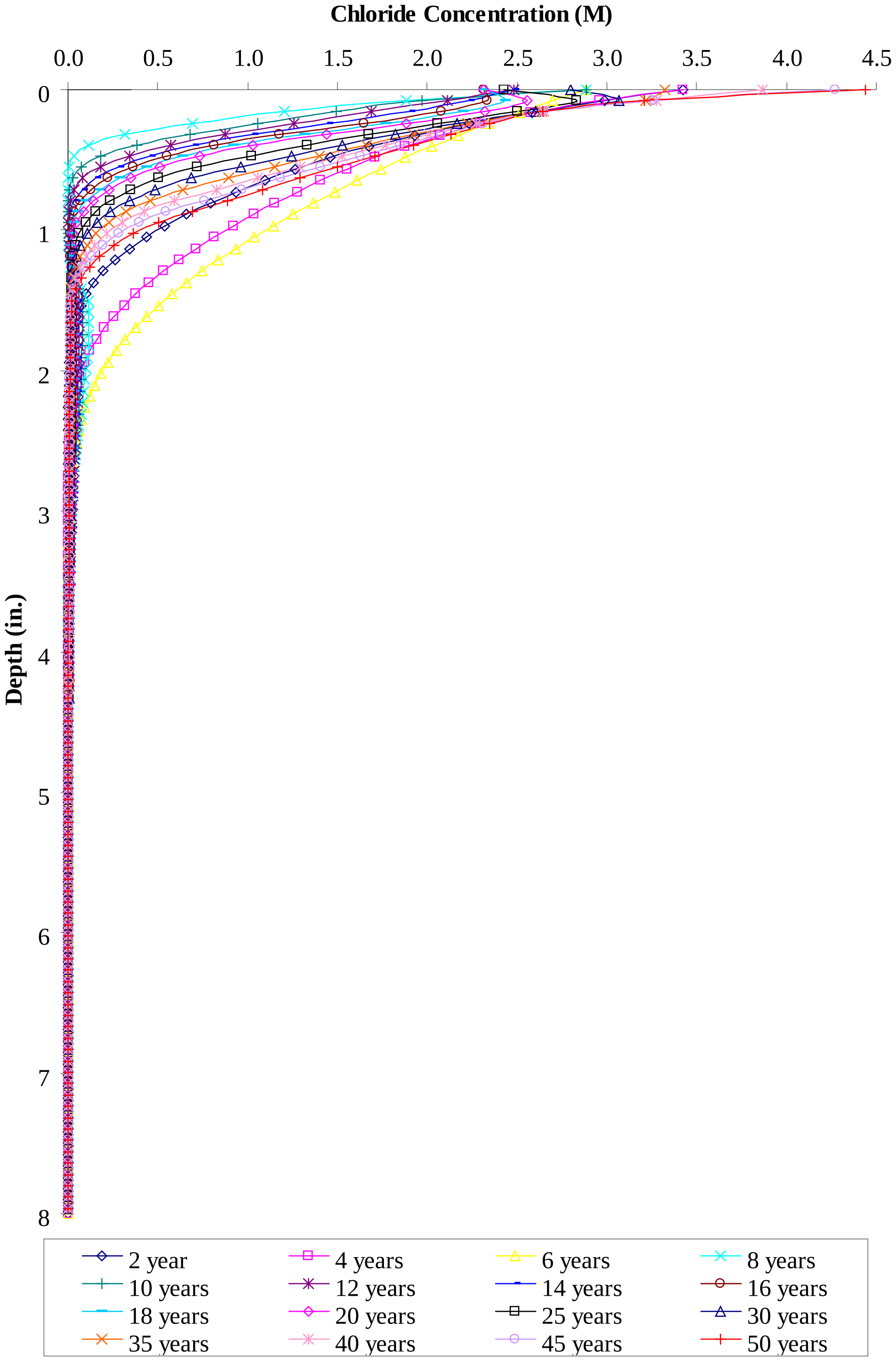

FIGURE D.5 Chloride concentrations of decks without SIPMFs with a 2.0-in. OCD and 1.5-in. scarification and 1.5-in. overlay treatment applied at 6 years.

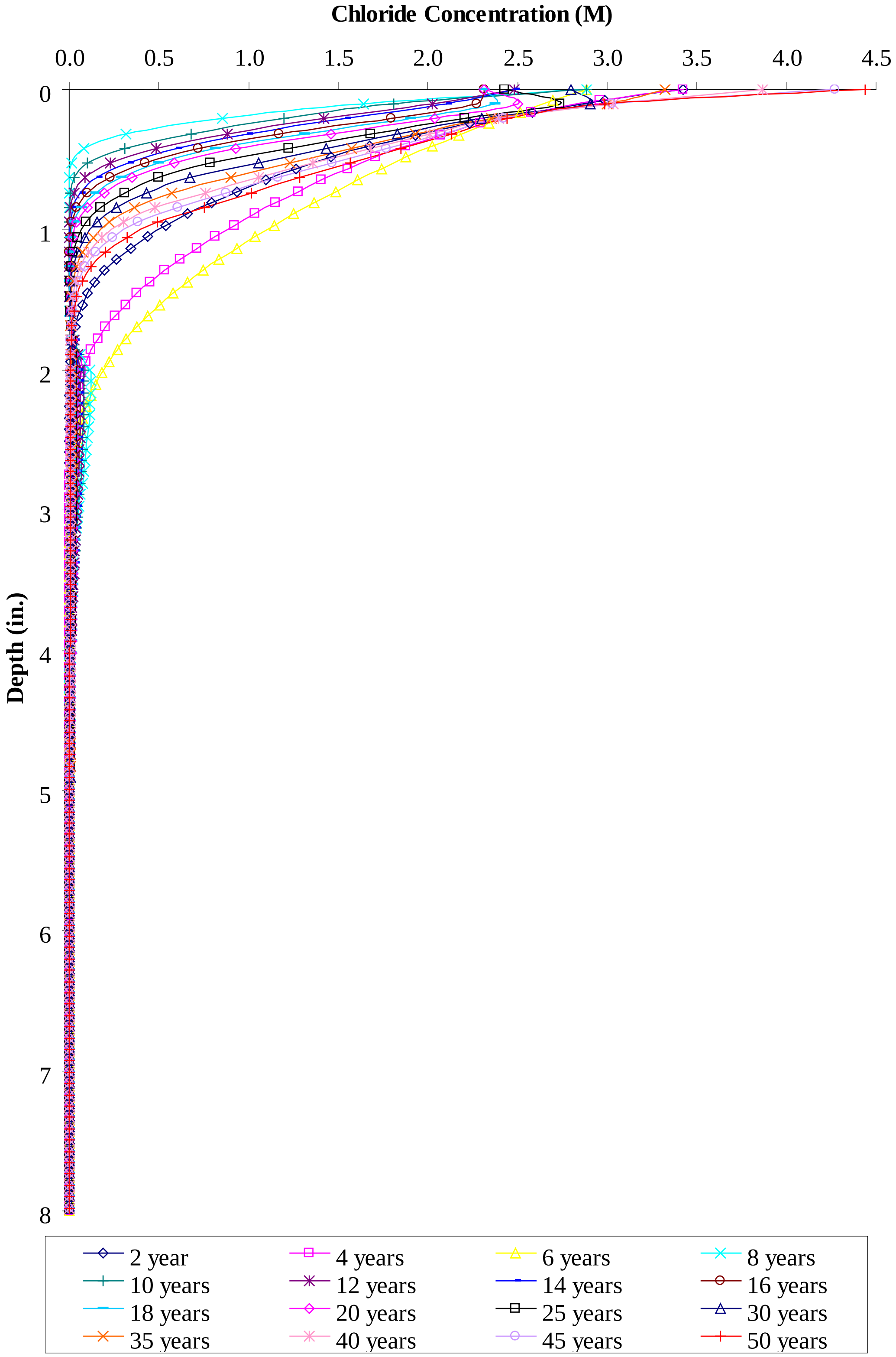

FIGURE D.6 Chloride concentrations of decks without SIPMFs with a 2.0-in. OCD and 1.5-in. scarification and 2.0-in. overlay treatment applied at 6 years.

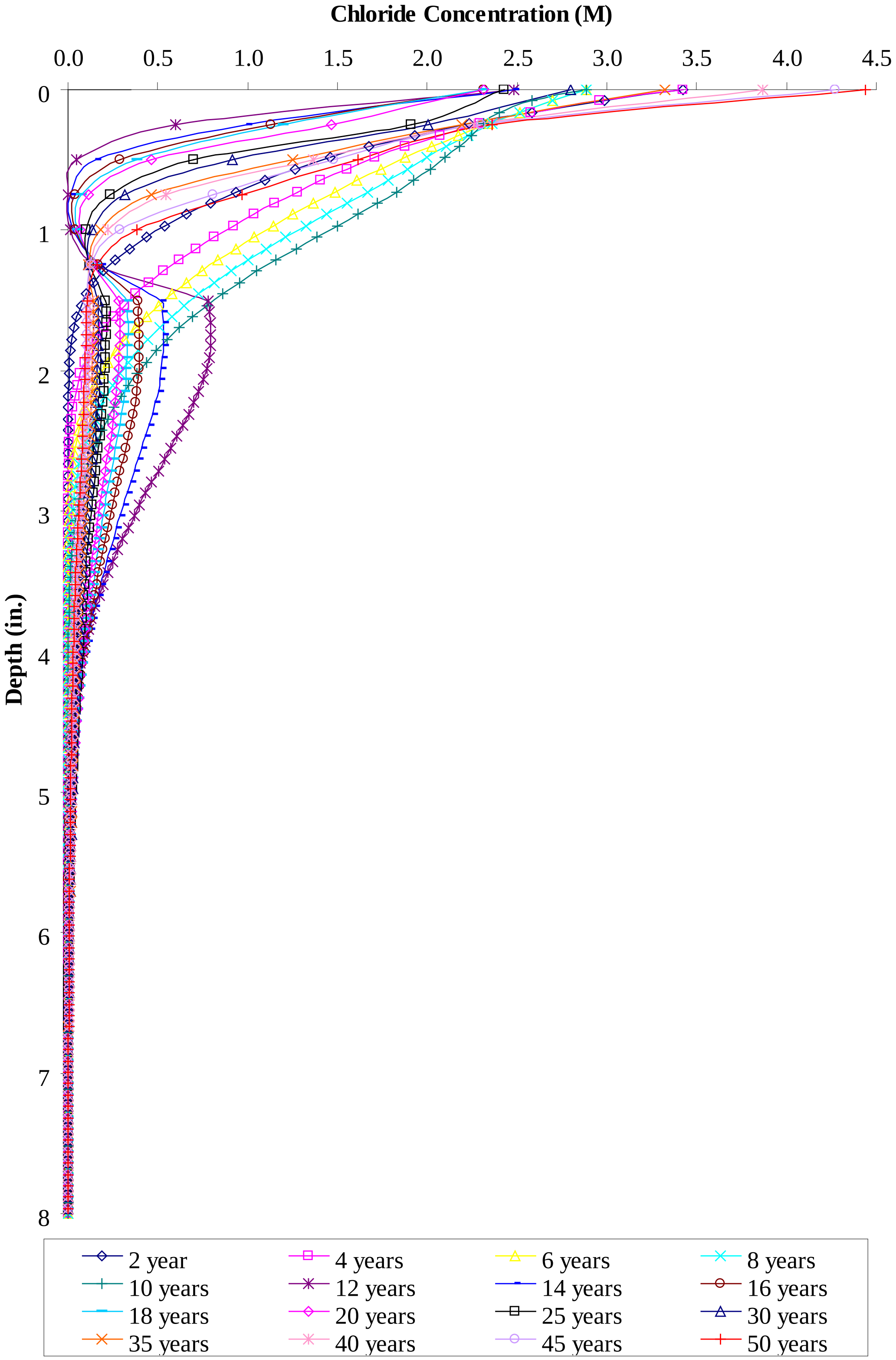

FIGURE D.7 Chloride concentrations of decks without SIPMFs with a 2.5-in. OCD and 0.5-in. scarification and 1.5-in. overlay treatment applied at 10 years.

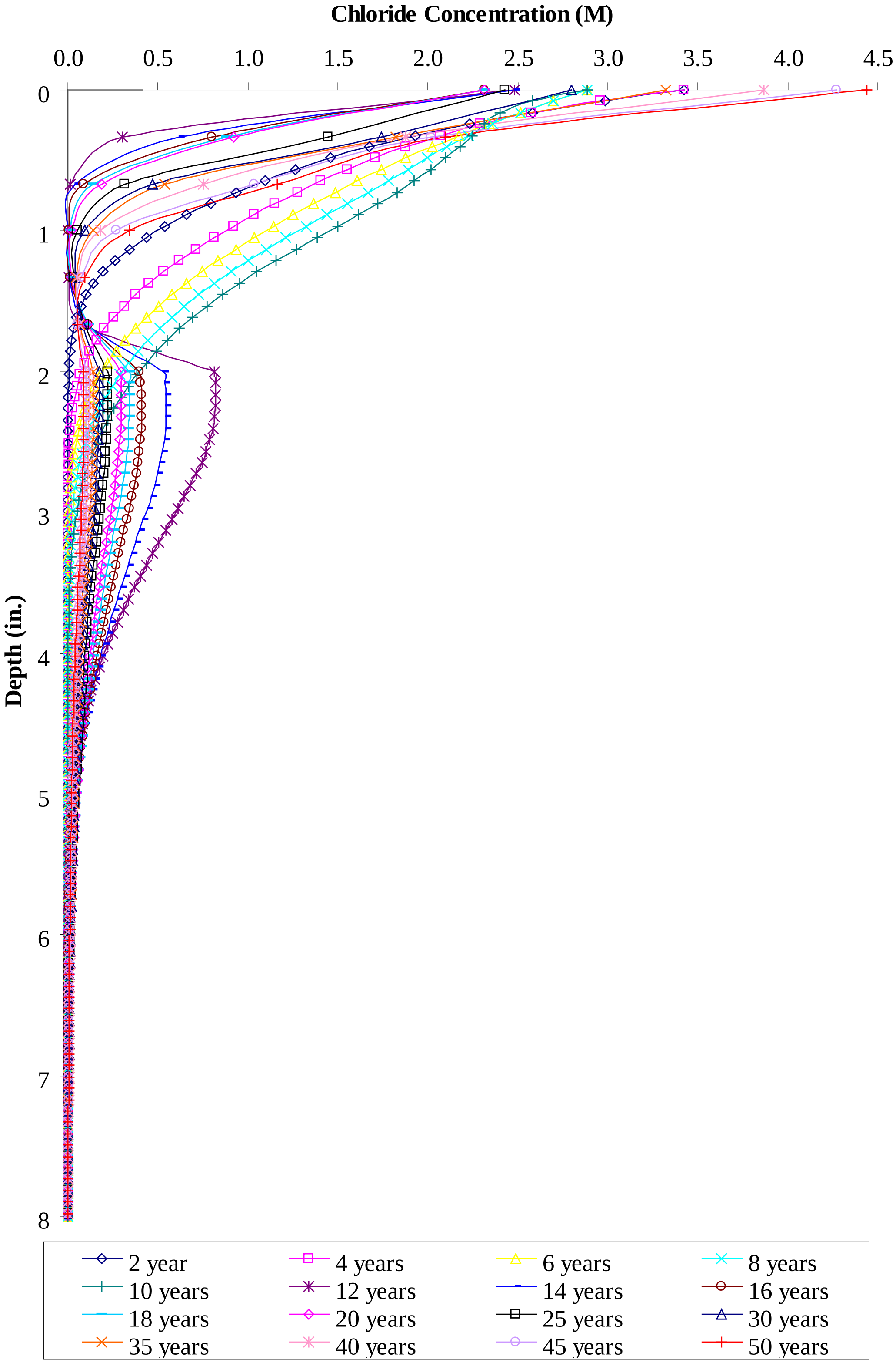

FIGURE D.8 Chloride concentrations of decks without SIPMFs with a 2.5-in. OCD and 0.5-in. scarification and 2.0-in. overlay treatment applied at 10 years.

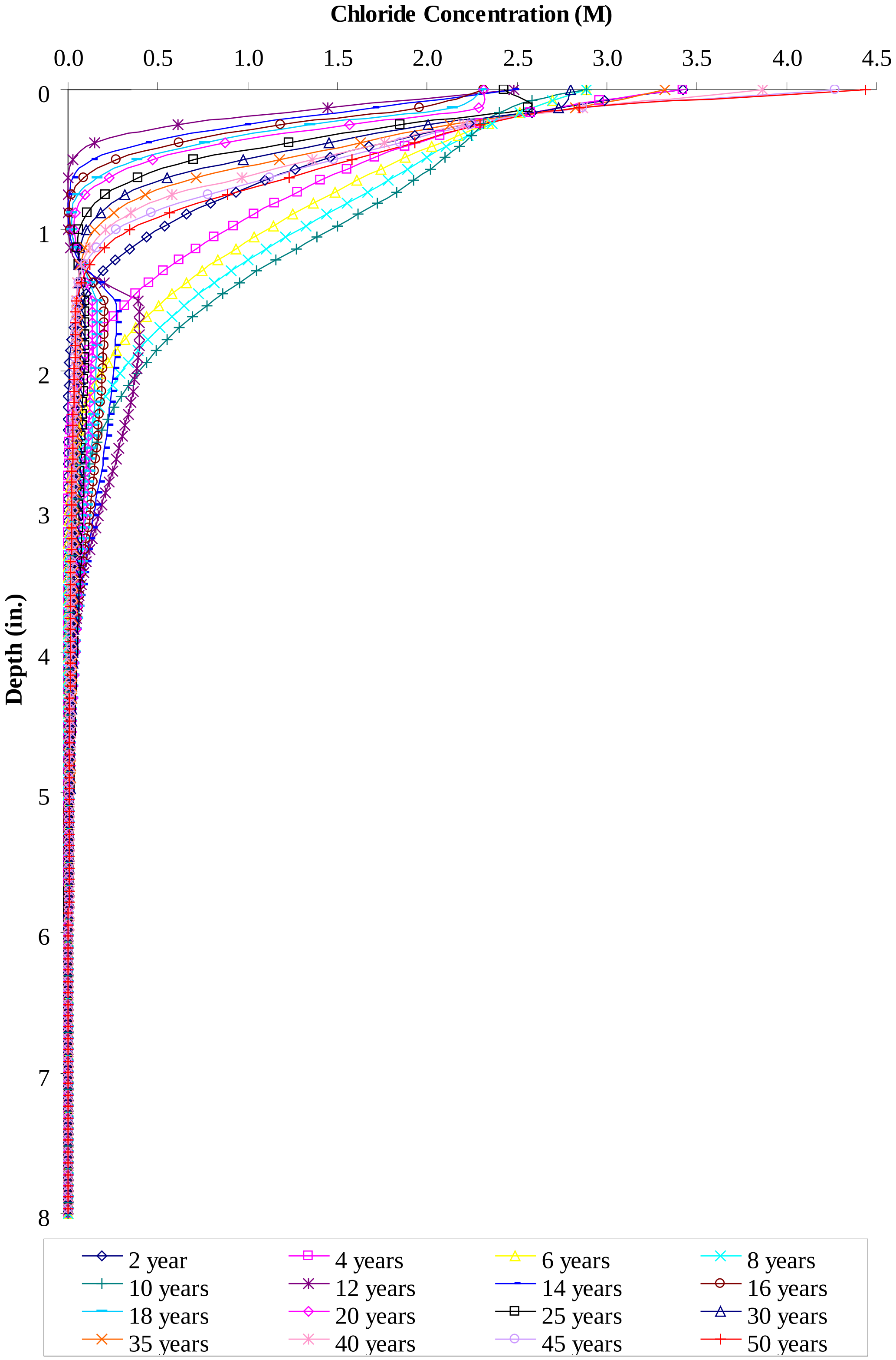

FIGURE D.9 Chloride concentrations of decks without SIPMFs with a 2.5-in. OCD and 1.0-in. scarification and 1.5-in. overlay treatment applied at 10 years.

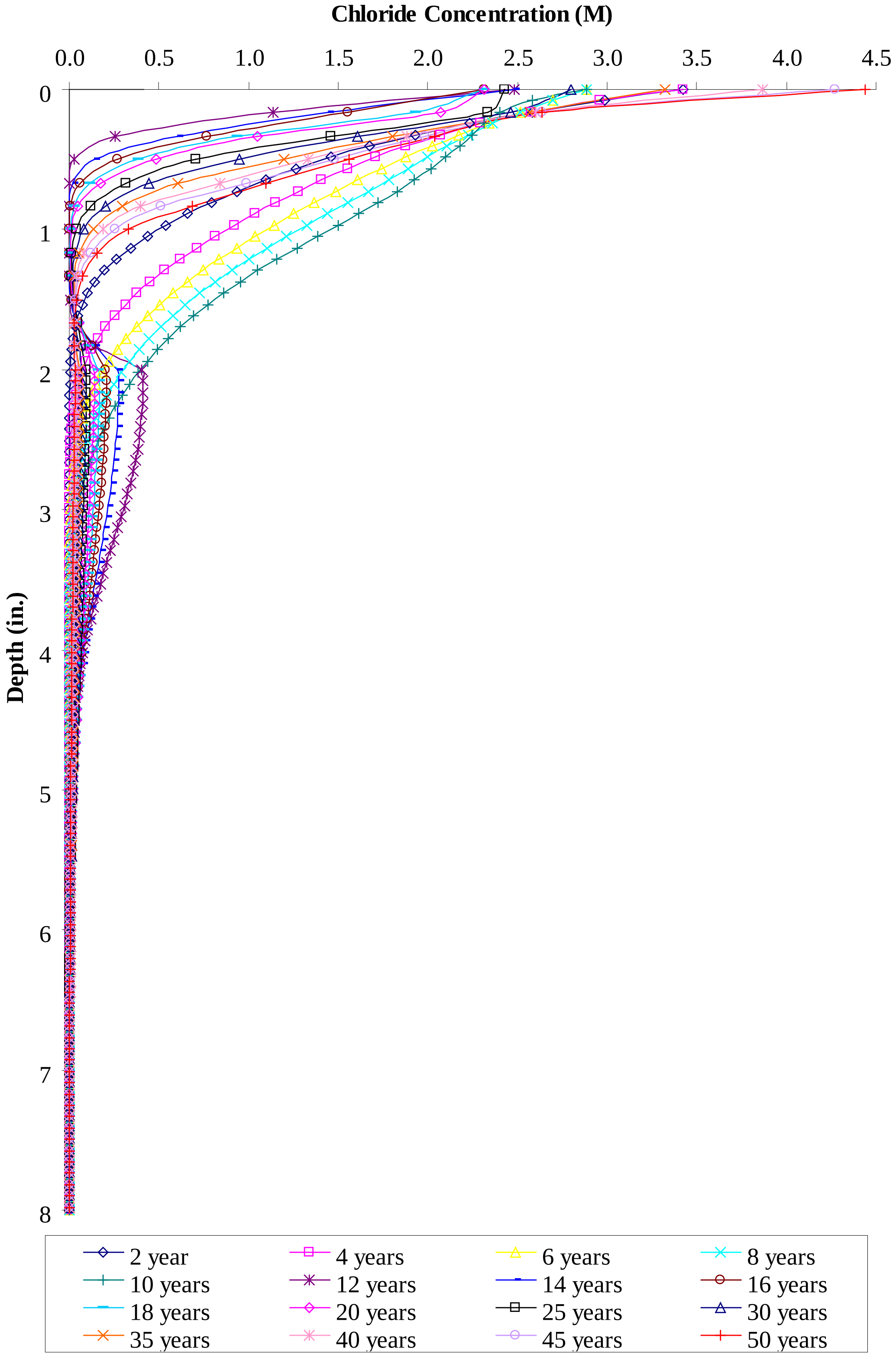

FIGURE D.10 Chloride concentrations of decks without SIPMFs with a 2.5-in. OCD and 1.0-in. scarification and 2.0-in. overlay treatment applied at 10 years.

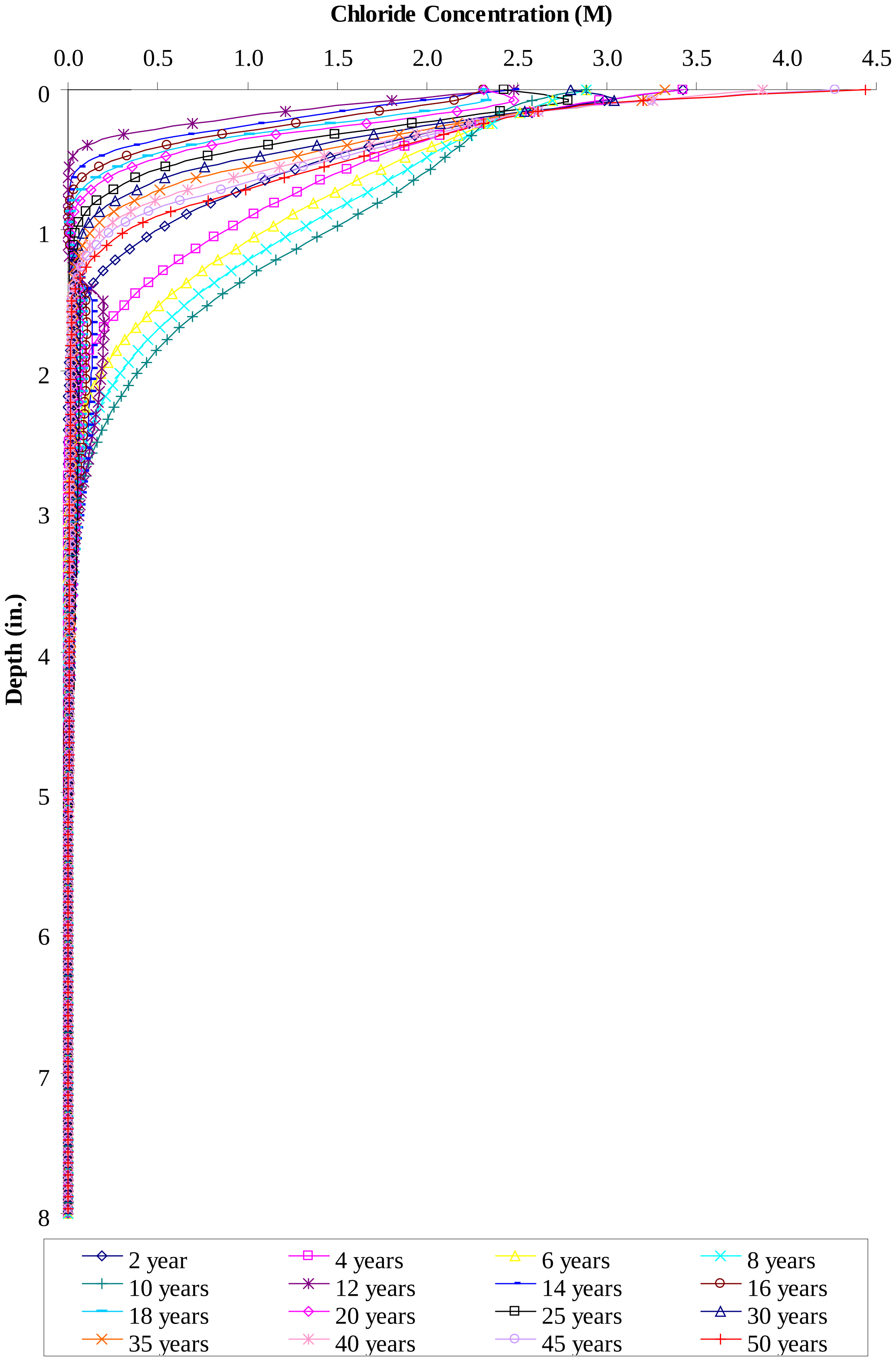

FIGURE D.11 Chloride concentrations of decks without SIPMFs with a 2.5-in. OCD and 1.5-in. scarification and 1.5-in. overlay treatment applied at 10 years.

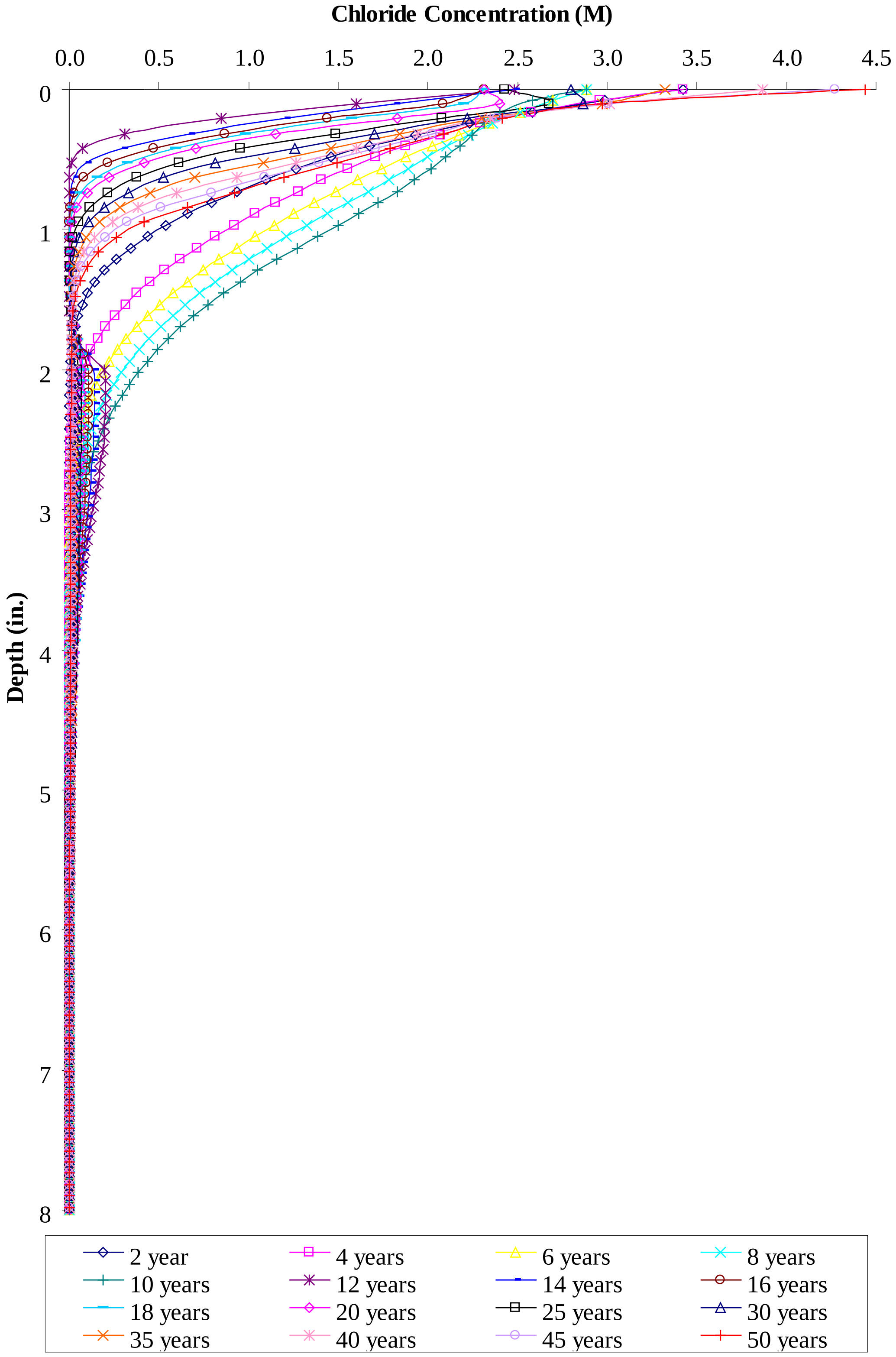

FIGURE D.12 Chloride concentrations of decks without SIPMFs with a 2.5-in. OCD and 1.5-in. scarification and 2.0-in. overlay treatment applied at 10 years.

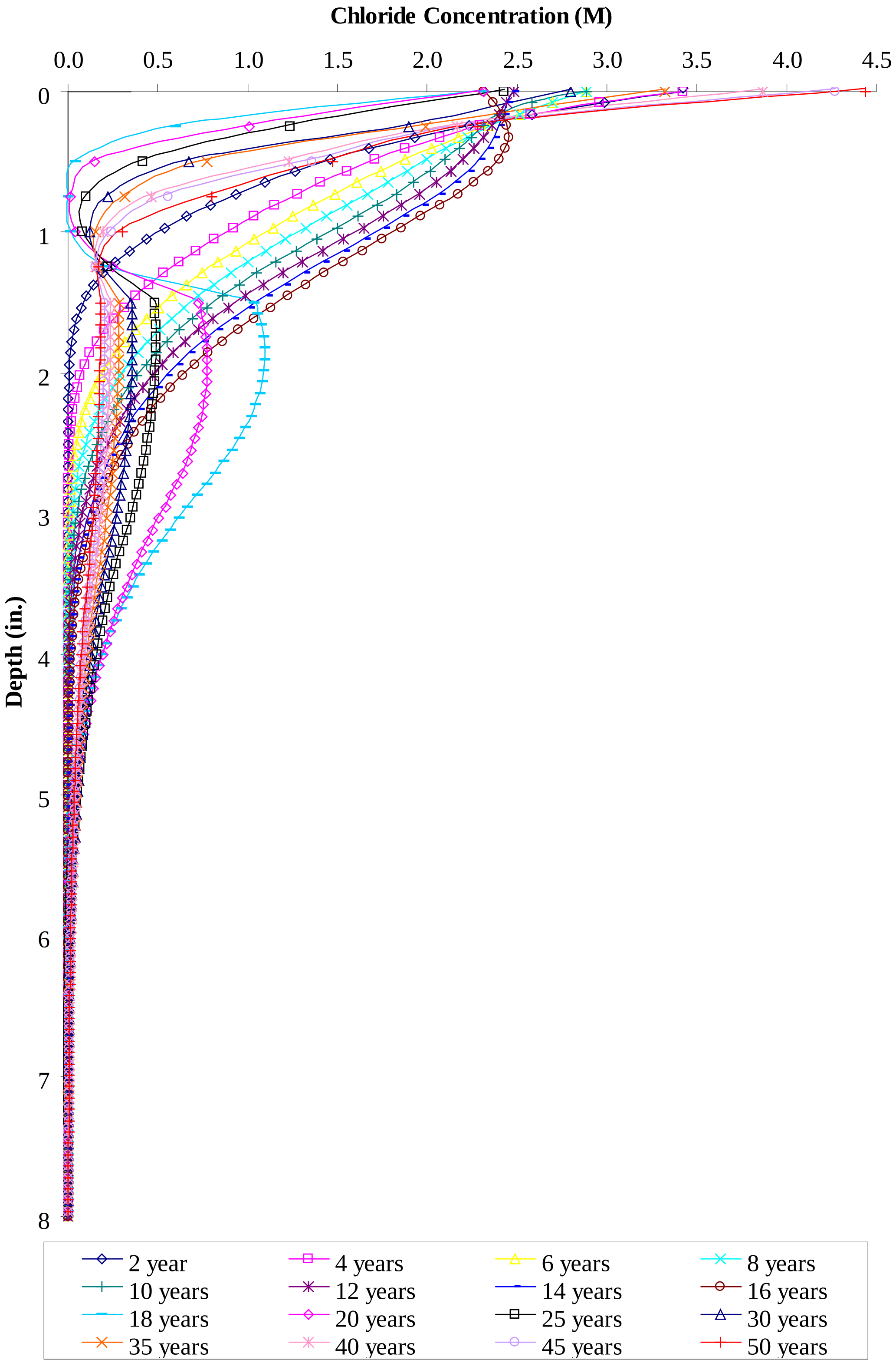

FIGURE D.13 Chloride concentrations of decks without SIPMFs with a 3.0-in. OCD and 0.5-in. scarification and 1.5-in. overlay treatment applied at 16 years.

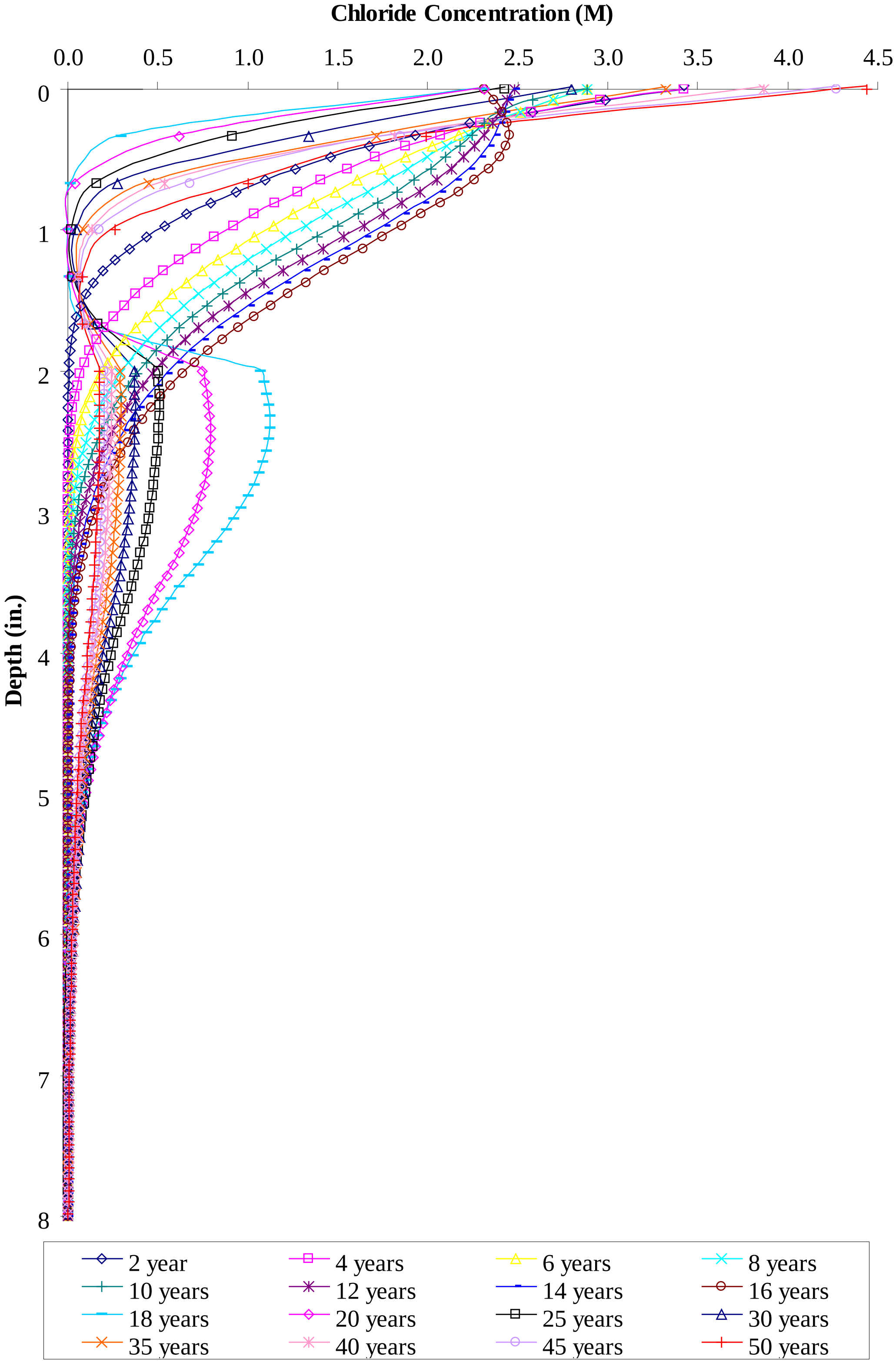

FIGURE D.14 Chloride concentrations of decks without SIPMFs with a 3.0-in. OCD and 0.5-in. scarification and 2.0-in. overlay treatment applied at 16 years.

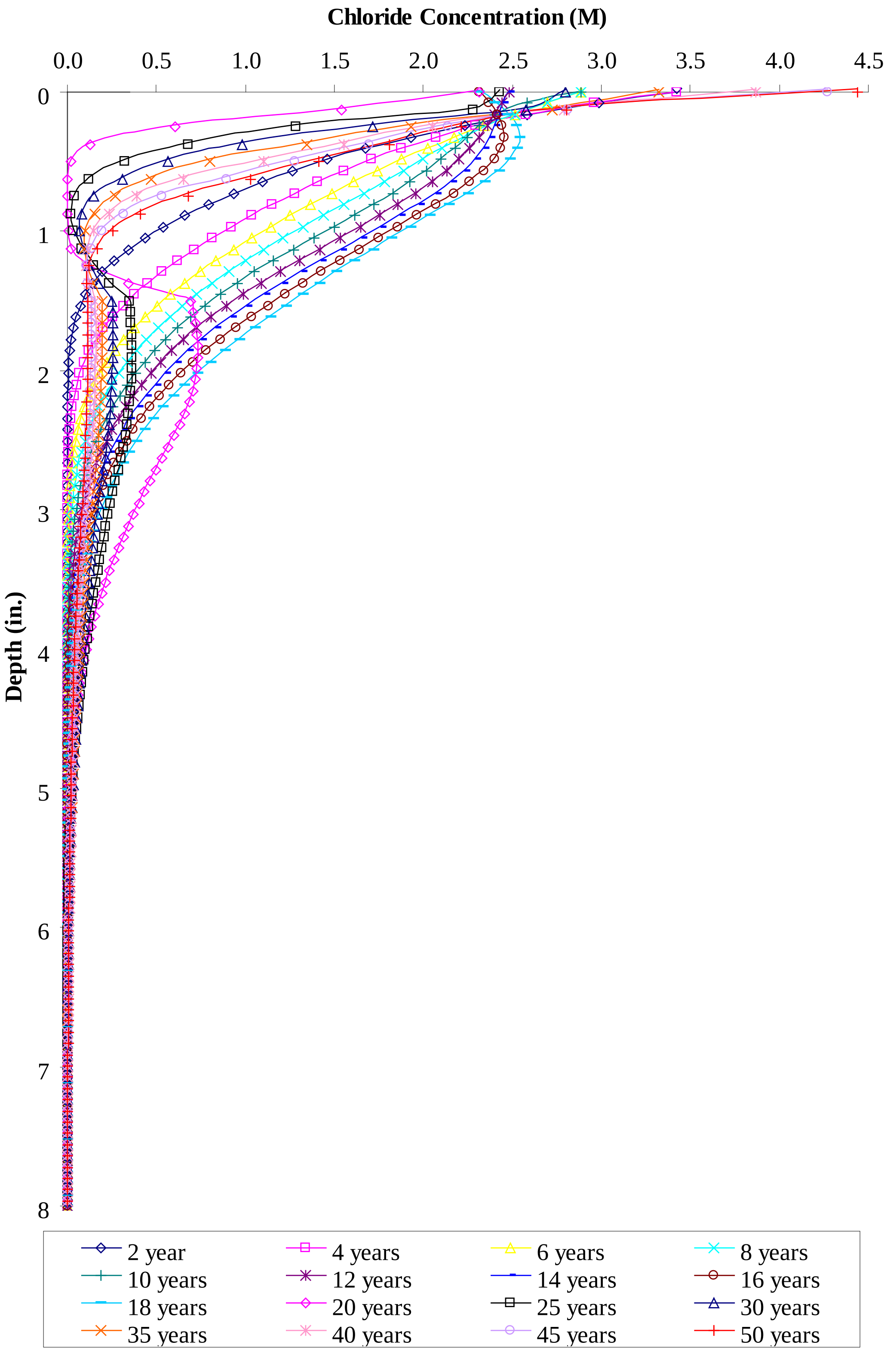

FIGURE D.15 Chloride concentrations of decks without SIPMFs with a 3.0-in. OCD and 1.0-in. scarification and 1.5-in. overlay treatment applied at 18 years.

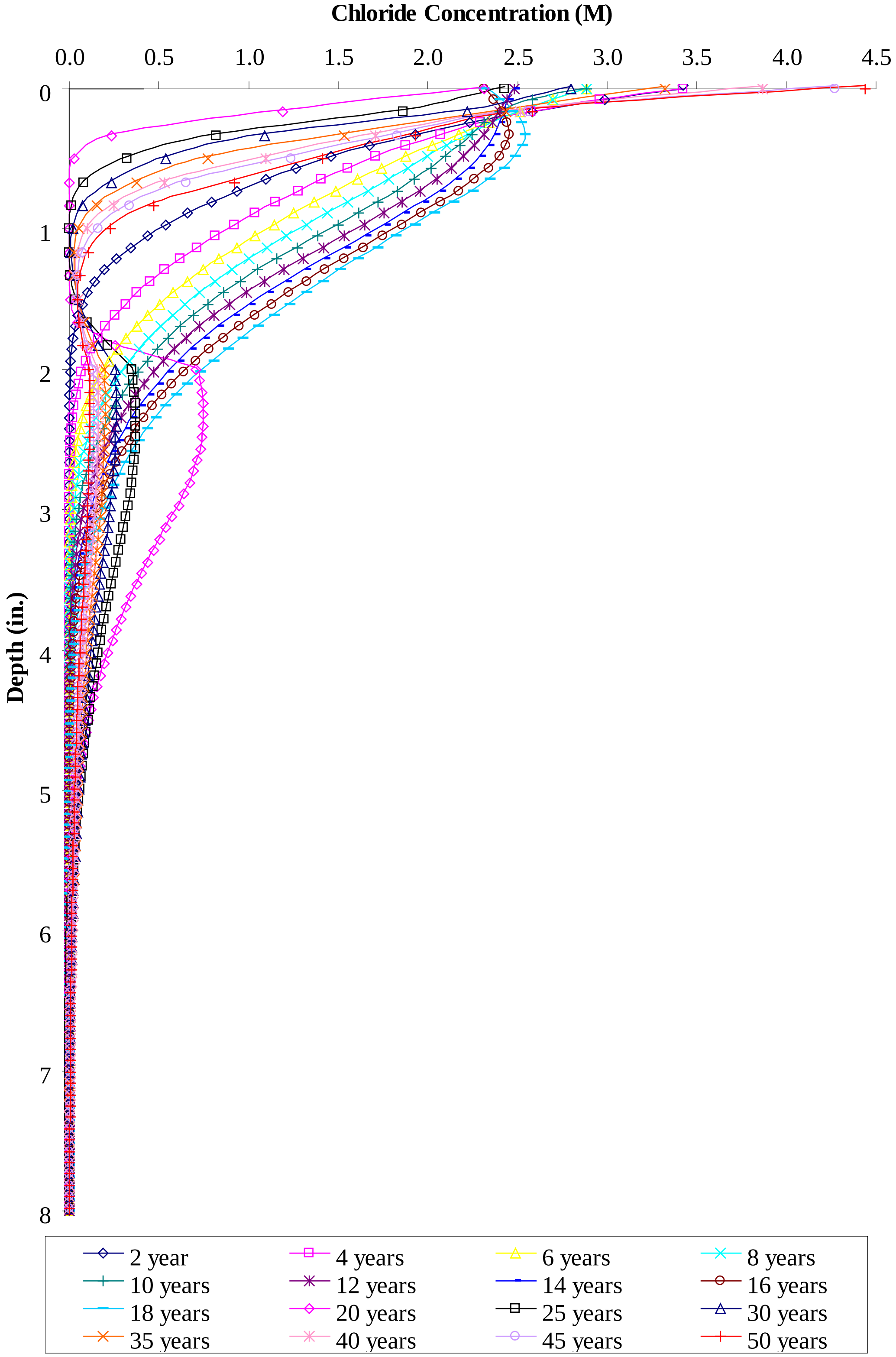

FIGURE D.16 Chloride concentrations of decks without SIPMFs with a 3.0-in. OCD and 1.0-in. scarification and 2.0-in. overlay treatment applied at 18 years.

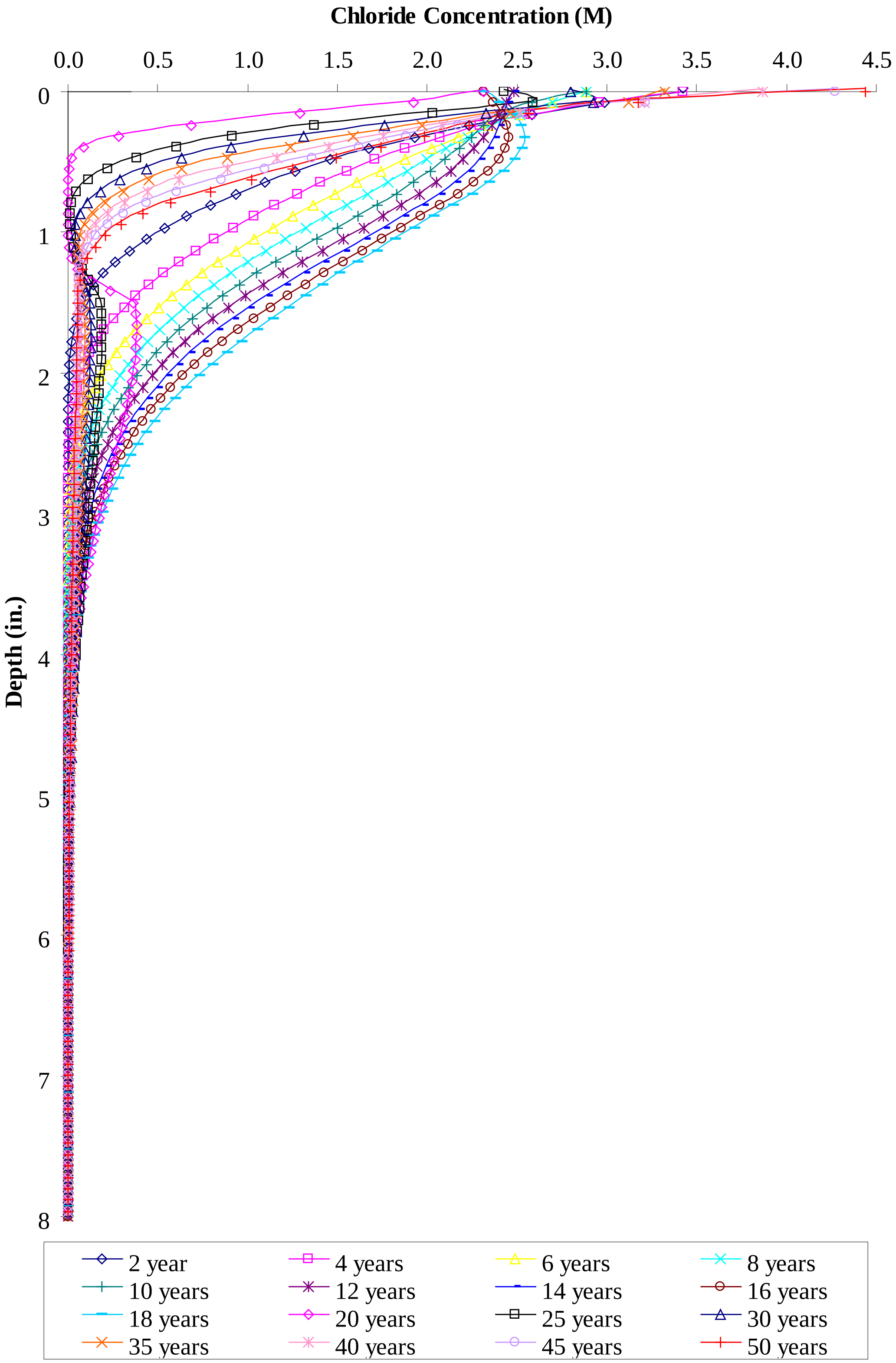

FIGURE D.17 Chloride concentrations of decks without SIPMFs with a 3.0-in. OCD and 1.5-in. scarification and 1.5-in. overlay treatment applied at 18 years.

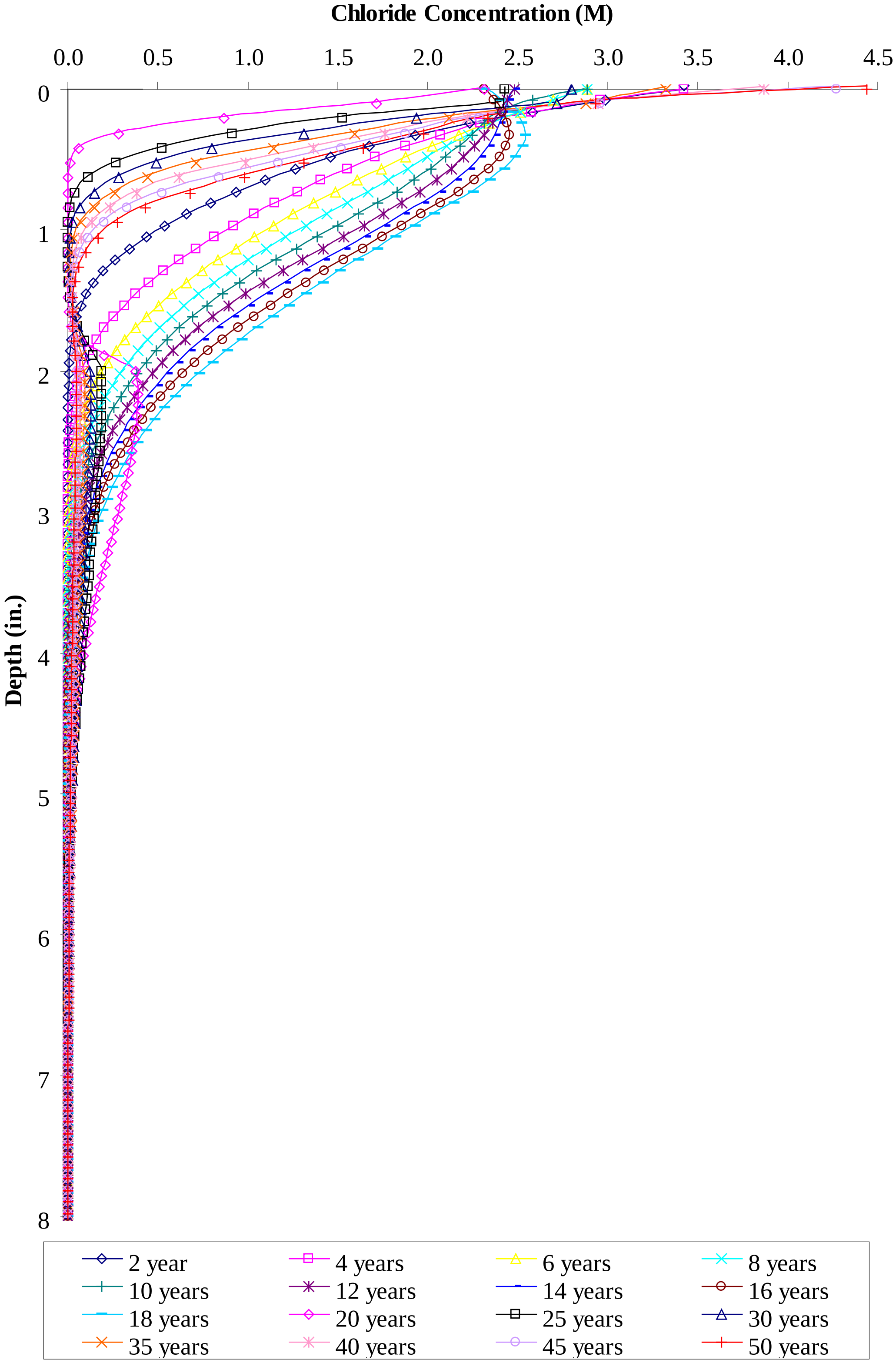

FIGURE D.18 Chloride concentrations of decks without SIPMFs with a 3.0-in. OCD and 1.5-in. scarification and 2.0-in. overlay treatment applied at 18 years.