2019-04-01

Estimating Phase Durations for Chloride-Induced Corrosion Damage of Concrete Bridge Decks in Utah

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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

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ABSTRACT

Estimating Phase Durations for Chloride-Induced Corrosion Damage
of Concrete Bridge Decks in Utah

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Chloride-induced deterioration of concrete bridge decks can be described in terms of three phases: 1) initiation of rebar corrosion, 2) rust formation and development of deck damage, and 3) accelerated deck damage towards structural failure. The first objective of this research was to investigate relationships among chloride concentration at the top mat of reinforcing steel, deck age, cover depth, and occurrence of delamination for concrete bridge decks with selected surface treatments and rebar types. Relating these factors can help establish greater understanding about the duration of each phase of the deterioration process. A second objective of this research was to investigate the relationship between chloride concentrations that develop between the bars and those that develop directly above the bars in the top mat of reinforcing steel to better understand the effects of the presence of reinforcing steel on diffusion of chloride ions through the concrete matrix.

Data collected from 48 concrete bridge decks in Utah were used to address both of the objectives stated for this research. Surface treatment types included bare concrete, thin-bonded polymer overlays, and asphalt overlays, and rebar types included uncoated and epoxy-coated rebar. Regarding the first objective, baseline relationships between chloride concentration, deck age, and cover depth were developed for all three deck types. The results show that, as deck age increases, chloride concentration also increases and that chloride concentrations are much higher for shallower concrete depths than for deeper concrete depths. Based on these relationships, the duration of the first phase of the deterioration process was estimated using the critical chloride threshold of 2.0 lb Cl^-/yd^3 of concrete. For decks with asphalt or polymer overlays, development of clear relationships between chloride concentration, deck age, and cover depth required consideration of treatment time. The data show that chloride concentrations for decks that had an overlay applied 10 or more years after construction are higher than those for decks that had an asphalt overlay applied immediately after construction.

Relevant to determining the duration of the second phase of the deterioration process, the relationship between delamination occurrence and chloride concentration for bare concrete bridge decks was developed. In general, the results show that the occurrence of delamination increases with increasing chloride concentration. Estimated durations of the second phase of the deterioration process were then determined using a chloride concentration threshold of 4.0 lb Cl^-/yd^3 of concrete for each of the same combinations of surface treatment and cover depth used for determining durations of the first phase of the deterioration process. Regarding the performance of epoxy-coated bar, the data clearly demonstrate the benefit of epoxy coatings on reinforcing steel for the purpose of significantly delaying the onset of chloride-induced delamination in concrete bridge decks.

The relationship between the ratio of chloride concentrations directly above and between steel reinforcing bars and deck age was then developed. The results show that, as deck age increases, the average ratio of chloride concentrations directly above and between the bars asymptotically decreases from above 1.5 toward 1.0, which is reached at a deck age of approximately 30 years. Given that increasing deck age generally corresponds to increasing chloride concentration, which would in turn eventually lead to similar chloride concentrations directly above and between bars as the concrete pore water within the cover depth approached chloride saturation, this observed relationship is consistent with theory.

Key words: asphalt overlay, chloride concentration, concrete bridge deck, delamination, epoxy-coated bar, polymer overlay

ACKNOWLEDGEMENTS

This research was supported and funded by the Utah Department of Transportation (UDOT). The author gratefully acknowledges assistance from members of the UDOT structures group as well as the Materials and Pavements Research Group at Brigham Young University. The author also thanks Dr. W. Spencer Guthrie, Dr. Gustavious P. Williams, and Dr. A. Woodruff Miller for serving on her graduate committee.

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1 INTRODUCTION

1.1 Problem Statement

Bridges are a critical component of the infrastructure in the United States. However, according to the infrastructure report card (ASCE 2017), 9.1 percent of the nation's bridges are considered structurally deficient, and nearly 40 percent of the existing bridges are at least 50 years old and therefore approaching the end of their design life. Thus, an increasing number of bridges will require rehabilitation or reconstruction in the coming years, with an estimated cost of $123 billion (ASCE 2017).

In cold regions, such as Utah, an important cause of structural deficiency is bridge deck deterioration resulting primarily from salt-induced corrosion of steel reinforcing bars, or rebar, embedded within the concrete (Bioubakhsh 2011, Gheitasi and Harris 2014, Guthrie and Tuttle 2006, Miller 2010, Russell 2004). Of the two mats of rebar typically present in a concrete bridge deck, the top mat is more susceptible to corrosion because of its closer proximity to the top deck surface, where deicing salts are applied as part of winter maintenance operations to maintain adequate skid resistance. The salts, which are commonly chloride-based compounds, reduce the formation of ice when they dissolve in water on the deck surface. However, the chloride ions then travel downward through the porous concrete matrix into the deck. Corrosion of the rebar is initiated when the chloride ions in contact with the rebar reach a critical concentration threshold of 2.0 lb Cl^-/yd^3 of concrete (Hema et al. 2004). As the corrosion process continues, the volume of the corrosion products, or rust, expands to a volume greater than that of the original steel

(Bioubakhsh 2011, McCarthy et. al. 2004). The low tensile strength of concrete and the increasing volume of rust can subsequently cause concrete cracking, which in turn leads to accelerated chloride ingress and further structural damage.

This deterioration process can be described in terms of three phases: 1) initiation of rebar corrosion, 2) rust formation and development of deck damage, and 3) accelerated deck damage towards structural failure. Because different bridge deck treatments are appropriate during each of these phases (Guthrie et al. 2007, Nelsen 2005), estimating the phase durations, so that the costs of bridge deck maintenance, rehabilitation, and reconstruction (MR&R) can be anticipated, is important for effective bridge deck management. A primary means of estimating phase durations is modeling, which is especially valuable when based on actual field data.

While several efforts have been made to model the overall bridge deck deterioration process (Hearn and Shim 1996, Hong et al. 2006, Morcous et al. 2002, Ramey and Wright 1994, Williamson et al. 2007), only selected efforts have focused on specific phases. Furthermore, as explained in Chapter 2, several assumptions inherent in those efforts limit the general application of the developed models. Accurately estimating the durations of the three phases of the deterioration process for concrete bridge decks in a particular region requires consideration of the effects of various factors, such as cover depth, application of deicing salts, and use of epoxy-coated reinforcement or surface treatments, that may be specific to that region. Development of such a model for the state of Utah was requested by the Utah Department of Transportation (UDOT) to inform statewide bridge deck management practices.

1.2 Research Objectives and Scope

The first objective of this research was to investigate relationships among chloride concentration at the top mat of reinforcing steel, deck age, cover depth, and occurrence of delamination for concrete bridge decks with selected surface treatments and rebar types. Relating these factors can help establish greater understanding about the duration of each phase of the deterioration process. A second objective of this research was to investigate the relationship between chloride concentrations that develop between the bars and those that develop directly above the bars in the top mat of reinforcing steel to better understand the effects of the presence of reinforcing steel on diffusion of chloride ions through the concrete matrix.

This research includes extensive data collected from 48 concrete bridge decks in Utah that were tested by the Materials and Pavements Research Group at Brigham Young University (BYU) between the years 2004 and 2017. As an example, Figure 1-1 shows one of the concrete bridge decks evaluated in the study. The deck age ranged from 0 to 47 years at the time of testing. For this research, surface treatment types included bare concrete, thin-bonded polymer overlays, and asphalt overlays, and rebar types included uncoated bar and epoxy-coated bar. The

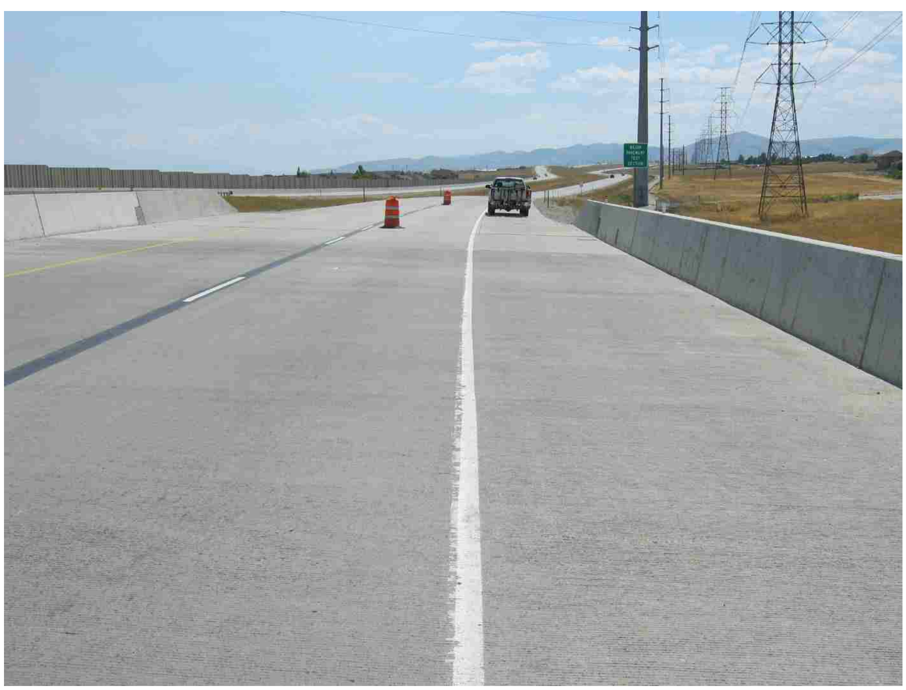

Figure 1-1: Bare concrete bridge deck.

bridge decks were analyzed using sounding, cover depth measurements, and chloride concentration testing.

1.3 Report Outline

This report contains five chapters. This chapter presents the problem statement, research objectives, and scope, and Chapter 2 provides background information relevant to the research objectives. Chapter 3 describes the experimental methodology, and Chapter 4 presents the results of the analyses. Finally, Chapter 5 provides conclusions and recommendations based on the research findings.

2 BACKGROUND

2.1 Overview

This chapter provides a discussion developed from a literature review performed to investigate selected topics relevant to the objectives of this research. The topics include chloride-induced corrosion of reinforcing steel, the bridge deck deterioration process, and preventative measures used to extend bridge deck service life, such as the use of epoxy-coated reinforcement and the application of surface treatments.

2.2 Chloride-Induced Corrosion

A primary transport mechanism for chloride ions in concrete is diffusion. Diffusion is the process by which ions move from areas of higher concentration to areas of lower concentration within the concrete pore water (Ahmad 2003, Ann et al. 2007, Bioubakhsh 2011). In cold regions, such as Utah, concrete bridge deck surfaces are exposed to chloride ions in the form of deicing salts applied during the winter, as illustrated in Figure 2-1 (Bonansinga 2017). For a typical storm in Utah, the average spreading rate of sodium chloride deicing salt is 250 lb per lane mile (Guthrie and Thomas 2013). The diffusion process is initiated when these salts dissolve in water and form ionic solutions on the concrete bridge deck surface. Chloride ions then diffuse downward from the surface into the concrete matrix, which is comprised of interconnected pore spaces, and disperse to areas of lower concentration (Ann et al. 2007). Cracks accelerate the

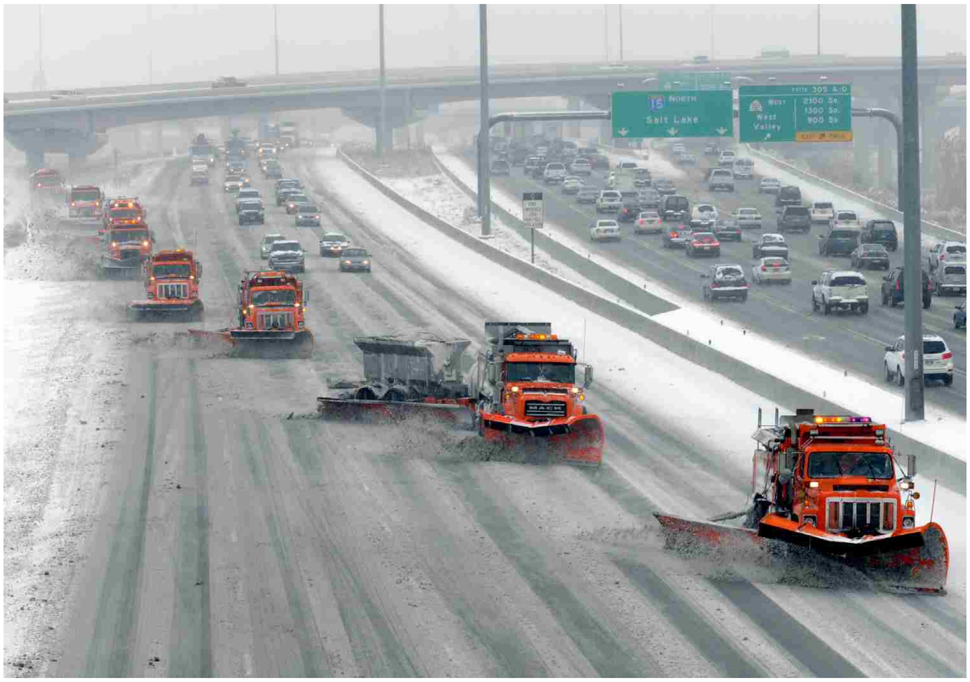

Figure 2-1: Application of deicing salt.

movement of chlorides by providing direct pathways for chloride ions to permeate the concrete matrix. The rate at which chloride ions diffuse through concrete pore water is highly dependent on the concrete material properties and the surface chloride concentrations, where greater porosity, higher moisture content, and higher surface chloride concentrations yield higher chloride diffusion rates (Birdsall et al. 2007). Conversely, the presence of an intact surface treatment can greatly reduce chloride ion ingress (Birdsall et al. 2007).

Reinforcing steel in concrete is normally protected from corrosion by a passive, oxide film that develops on the steel due to the alkaline environment provided by the surrounding concrete (Arup 1983). However, when chloride concentrations reach a critical threshold of 2.0 lb Cl^-/yd^3 of concrete, the alkalinity of the concrete can be reduced, and the passive, oxide layer in the steel can break down (Bioubakhsh 2011, Hema et al. 2004, Melcher 2009). After this breakdown, a porous, oxide layer forms around the steel as localized corrosion begins.

During the corrosion period, the cross-sectional area of the intact reinforcing steel decreases as illustrated in Figure 2-2, which shows heavily corroded reinforcing steel exposed during hydrodemolition of a concrete bridge deck that had been subject to deicing salt applications for more than 40 years (Guthrie et al. 2014). The reduction in cross-sectional area is attended by the development of tensile stresses in the concrete due to the expanding volume of the corrosion products, which can occupy two to six times the volume of the original steel (Fanous et al. 2000, Suda et al. 1993, Mindess et al. 2003). These tensile stresses can cause the concrete to crack and separate from the reinforcement, resulting in delamination as depicted in

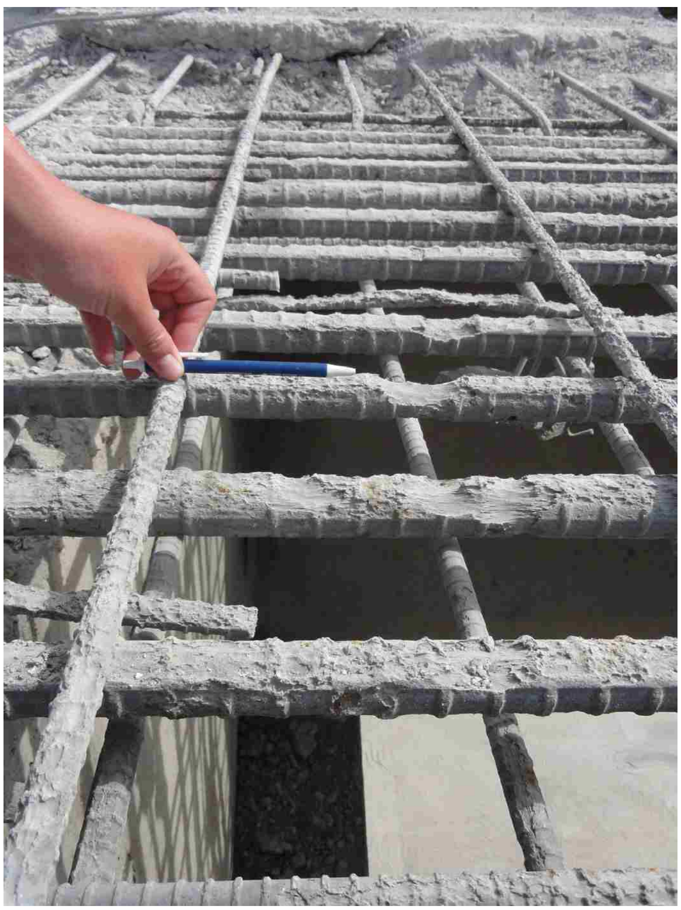

Figure 2-2: Corroded reinforcing steel in a concrete bridge deck.

Figure 2-3, which shows a delaminated concrete bridge deck slab removed from a decommissioned bridge (Sumsion 2013). For a given environment, the location and extent of damage caused by delamination are dependent on geometrical properties of the bridge deck, such as cover depth, rebar spacing, and rebar diameter (Ghetasi 2014). Delamination reduces the structural integrity of the bridge deck at affected locations and may lead to premature deck failure. Departments of transportation (DOTs) indicate that deck repair is required when delamination affects 5 to 20 percent of the total deck area and that deck replacement is required when delamination affects 30 to 50 percent of the total deck area (Guthrie and Hema 2004).

Figure 2-3: Delaminated concrete bridge deck slab.

2.3 Deterioration Process

The deterioration process can be divided into three phases: 1) initiation of rebar corrosion, 2) rust formation and development of deck damage, and 3) accelerated deck damage towards structural failure. The model shown in Figure 2-4 schematically illustrates the effects of the deterioration process on the relationship between deck condition and deck age. The first phase, which is indicated by “I” in Figure 2-4, is defined as the time between deck construction and initiation of rebar corrosion (Ahmad 2003). As previously mentioned, rebar corrosion is initiated when the chloride ions in contact with the rebar reach a critical concentration threshold of 2.0 lb Cl^-/yd^3 of concrete. The presence of cracks in the concrete can shorten the initiation period and

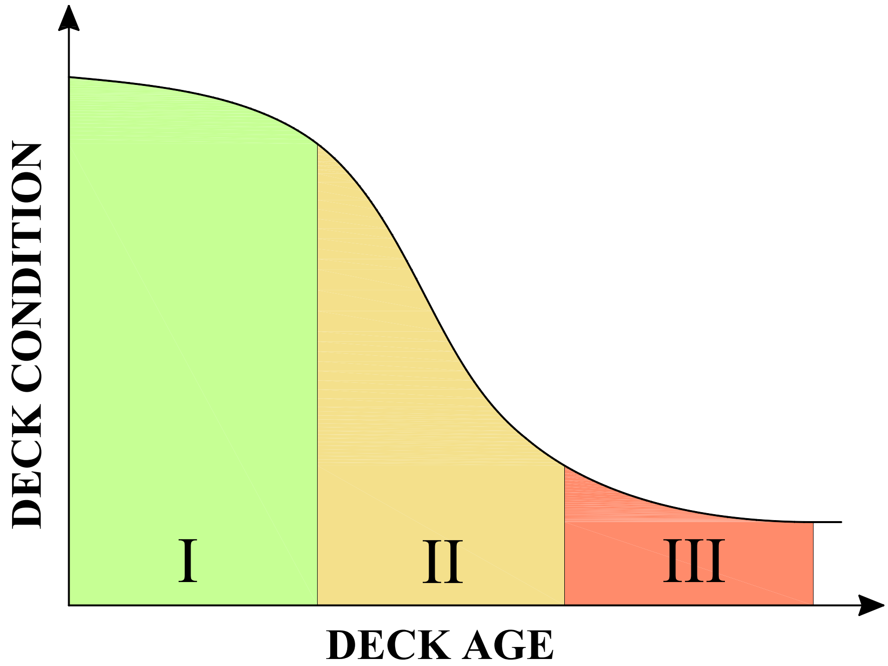

Figure 2-4: Concrete bridge deck deterioration model.

accelerate the rate of corrosion (Ghetasi 2014). The second phase of the deterioration process, indicated by “II” in Figure 2-4, is defined as the time between initiation of rebar corrosion and development of deck damage. During this phase, various forms of deck distress, including cracking, delamination, and spalling, develop as a result of the formation of rust on the steel reinforcement (Bu 2015). As previously noted, the occurrence of delamination, which precedes spalling, is an indicator of structural deficiency. The third and final phase of the deterioration process, which is indicated by “III” in Figure 2-4, is defined as the time between development of deck damage and structural failure. The progression of deterioration can require frequent maintenance of the bridge deck to provide satisfactory serviceability during this phase. The bridge deck should be scheduled for major rehabilitation or reconstruction before structural failure becomes imminent.

While several efforts have been made to model the overall bridge deck deterioration process, generally by applying statistical techniques to historical data (Hearn and Shim 1996, Hong et al. 2006, Morcous et al. 2002, Ramey and Wright 1994, Williamson et al. 2007), only selected efforts have focused on specific phases. Regarding the first phase, Fick's second law of diffusion has been used to predict when the chloride concentration may reach the critical threshold of 2.0 lb Cl^-/yd^3 of concrete (Ahmad 2003, Bentz et al. 2014, Birdsall et al. 2007, Guthrie et al. 2011). However, the application of Fick's second law is limited by several assumptions (Morcous et al. 2002), and the actual presence of rebar is typically ignored in chloride ion diffusion calculations. Regarding the second phase, while models have been developed to estimate when bridge decks will begin to exhibit corrosion-induced damage such as internal cracks, surface cracks, delamination, and spalling (Lindquist 2005, Lounis and Daigle 2008), these models are limited in their applications to decks with specific overlay types or environmental conditions, for example, and/or lack validation using field data. Regarding the third phase, models have been developed that generally estimate the remaining bridge deck service life using temporal trends in the National Bridge Inventory (NBI) ratings and/or limited field data (Bu 2015, Hong et al. 2006, Mauch and Madanat 2001). However, while valid field data are very useful for modeling, results derived from NBI ratings are inherently subjective because the NBI rating system is based mainly on visual assessment; therefore, given that the results are subjective and deterioration mechanisms are not detected until the damage becomes visible (Bu 2015), deterioration models based on NBI ratings may not accurately reflect the condition of a bridge deck, especially in the first and second phases of the deterioration process. Accounting for important deterioration factors, such as cover depth, application of deicing salts, and use of epoxy-coated reinforcement or surface treatments can help establish greater understanding about the length of time that bridge decks may spend in each phase of the deterioration process.

2.4 Preventative Measures

Two commonly practiced preventative measures include the use of epoxy-coated reinforcement and the application of surface treatments to bridge decks. The main purpose of these preventative measures is to delay the initiation of rebar corrosion within concrete bridge decks as described in the following sections.

2.4.1 Epoxy-Coated Reinforcement

Over the past 50 years, the use of epoxy-coated reinforcement has been a standard practice in many cold regions to mitigate corrosion in concrete bridge decks. The epoxy coating is specifically intended to protect the rebar from exposure to oxygen, water, and chloride ions (Brown et al. 2003). Figure 2-5 shows the top and bottom mats of epoxy-coated reinforcement installed during construction of a new bridge deck, prior to concrete placement. In one study based on extensive field experimentation, the expected service life of a bridge deck with epoxy-coated reinforcement has been estimated to be nearly double that of decks with uncoated reinforcement (Boatman 2010). However, other studies also based on field experimentation have concluded in one case that the use of epoxy-coated reinforcement extends the service life of a bridge deck by only 5 years and in another case that it may provide protection for only 5 percent of all bridge decks (Brown et al. 2003, Weyers et al. 1998). The apparent discrepancy may be attributable not only to variation in the quality of epoxy coating applications but also to varying levels of care during handling by contractor personnel during rebar placement at the time of deck

Figure 2-5: Epoxy-coated reinforcement.

construction (Guthrie et al. 2008). If the epoxy coating on the reinforcement is damaged, the reinforcement will be unprotected, and localized corrosion can ensue (Fanous et al. 2000). Given that some data suggest that corrosion can occur even under an apparently intact epoxy coating when the chloride concentration is sufficiently high (Weyers et al. 1998), epoxy coatings must be applied to rebar with uniformly high quality, and epoxy-coated reinforcement must be handled with care during construction operations to ensure optimal corrosion protection.

2.4.2 Surface Treatments

Application of surface treatments is another method used to delay the initiation of rebar corrosion within concrete bridge decks. While surface treatments have limited efficacy during the second and third phases of the deterioration process, when chloride concentrations have already reached or exceeded the corrosion threshold at the level of the top mat of reinforcing steel, they have been shown to be highly effective during the first phase (Birdsall et al. 2007). When they are installed correctly, surface treatments delay corrosion initiation by sealing the deck against the ingress of water and chloride ions (Bioubakhsh 2011). Asphalt and polymer overlays, which are depicted in Figures 2-6 and 2-7, respectively, are two surface treatments that have been commonly utilized in Utah to prevent chloride-induced corrosion in concrete bridge decks (De Leon 2018).

Historically, asphalt overlays were frequently applied to bridge decks in Utah. An asphalt overlay system typically consists of a bonding primer, a waterproofing membrane, and two hot mix asphalt layers (Krauss et al. 2009). The waterproofing membrane is placed at the interface between the deck surface and the lower asphalt layer to serve as a barrier against moisture and chloride ion penetration. The typical thickness of an asphalt overlay is 2.5 in. to 3.0 in. (Lachemi

Figure 2-6: Deck with asphalt overlay.

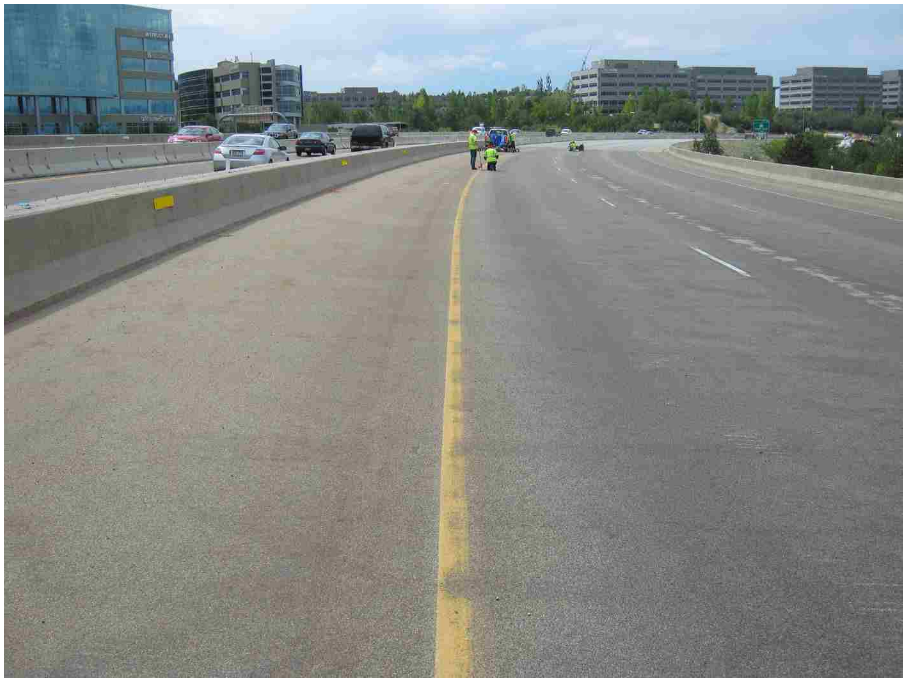

Figure 2-7: Deck with polymer overlay.

et al. 2007), and the installation process takes approximately 3 days, depending on the size of the bridge (Krauss et al. 2009). In a National Cooperative Highway Research Program questionnaire survey about the effectiveness of asphalt overlays, the respondents indicated that they expected asphalt overlays with waterproofing membrane systems to last 16 to 20 years when installed at the time of deck construction and 6 to 20 years when installed on bridge decks already in service. In the latter case, existing deck damage can lead to earlier failure, especially of the waterproofing membranes that are applied to the deck surface. Failure is commonly manifest as lack of adhesion between the membrane, asphalt overlay, and concrete bridge deck and/or tears in the membrane that lead to overlay cracking, as shown in Figure 2-8, and subsequent penetration of moisture and chloride ions, which ultimately reduces the service life of the affected bridge decks (Bioubakhsh 2011, Russell 2012).

Figure 2-8: Cracking of asphalt overlay.

Polymer overlays are becoming increasingly popular in Utah due to their minimal thickness and rapid installation (De Leon 2018). A polymer overlay consists of a thin layer of usually epoxy-based polymer and a surface coating of fine aggregate (Shearrer et al. 2015). The typical thickness of a polymer overlay is 0.25 in. to 0.75 in., and the installation process takes less than 24 hours (Krauss et al. 2009, Tabatabai et al. 2016). Polymer overlays are approximately 10 times more effective in resisting chloride ingress than bare concrete (Pan et al. 2017). However, re-application of a polymer overlay approximately every 10 years is required to maintain effectiveness (Guthrie et al. 2005). Premature failure is usually manifest as delamination of the overlay, as illustrated in Figure 2-9 (Guthrie et al. 2005, Rogers et al. 2011).

Figure 2-9: Delamination of polymer overlay.

2.5 Summary

A primary transport mechanism for chloride ions in concrete is diffusion. During the corrosion period, the cross-sectional area of the intact reinforcing steel decreases, and tensile stresses develop in the concrete due to the expanding volume of the corrosion products. The deterioration process can be divided into three phases: 1) initiation of rebar corrosion, 2) rust formation and development of deck damage, and 3) accelerated deck damage towards structural failure. While several efforts have been made to model the overall bridge deck deterioration process, only selected efforts have focused on specific phases; accounting for important deterioration factors, such as cover depth, application of deicing salts, and use of epoxy-coated reinforcement or surface treatments can help establish greater understanding about the length of time that bridge decks may spend in each phase of the deterioration process. Two commonly practiced preventative measures for delaying the initiation of rebar corrosion within concrete bridge decks include the use of epoxy-coated reinforcement and the application of surface treatments to bridge decks.

3 PROCEDURES

3.1 Overview

Under the direction of UDOT, the BYU Materials and Pavements Research Group performed testing of 48 concrete bridge decks in Utah between the years 2004 and 2017. Of these 48 bridge decks, nine were tested more than once. The decks, which ranged from 0 to 47 years old at the time of testing, were subject to similar climatic conditions and maintenance routines, including the application of chloride-based deicing salts during the winter. Forty of the bridge decks were constructed with epoxy-coated reinforcement, while eight were constructed with uncoated reinforcement, commonly referred to as black bar. At the time of testing, the decks had bare concrete surfaces, polymer overlays, asphalt overlays, and/or concrete overlays. In this research, polymer overlays include thin-bonded epoxy and healer/sealer applications, asphalt overlays include hot mix asphalt applications with or without a membrane, and concrete overlays include mainly latex-modified concrete applications. The locations of the tested bridges are shown in Figure 3-1, and relevant information about the bridge decks is shown in Table 3-1, in which “NA” indicates “not applicable.” For decks tested more than once, the surface treatment type is specified for each testing time. The procedures associated with the field data collection and data compilation and analysis are described in the following sections.

Figure 3-1: Bridge deck locations.

Table 3-1: Bridge Deck Data

Bridge ID	Surface Treatment Type	Reinforcement Type	Year of Deck Construction	Year of Surface Treatment Application	Year of Testing
C-357	Asphalt Overlay	Uncoated	1964	1972	2011
C-358	Asphalt Overlay	Uncoated	1964	1972	2011
C-363	Asphalt Overlay	Epoxy-Coated	1984	1973	2011
C-438	None	Epoxy-Coated	2003	NA	2005
C-460	None/ Asphalt Overlay	Epoxy-Coated	1988	2005	2005/ 2016
C-525	Polymer Overlay	Uncoated	1970	1976	2017
C-655	Polymer Overlay	Uncoated	1976	1976	2017
C-683	Polymer Overlay	Epoxy-Coated	1981	2006	2017
C-684	Polymer Overlay	Uncoated	1981	2006	2017
C-685	Polymer Overlay	Epoxy-Coated	1982	2006	2017
C-688	None	Epoxy-Coated	1987	NA	2016
C-698	None/ None	Epoxy-Coated	1987	NA	2005/ 2016
C-699	None	Epoxy-Coated	1987	NA	2016
C-725	None/ None	Epoxy-Coated	1984	NA	2015/ 2016
C-726	None	Epoxy-Coated	1984	NA	2016
C-736	Polymer Overlay	Epoxy-Coated	1987	1987	2005
C-752	Polymer Overlay	Epoxy-Coated	1988	2004	2005
C-754	None	Epoxy-Coated	1989	NA	2016
C-757	Polymer Overlay	Epoxy-Coated	1989	1989	2015
C-759	Polymer Overlay/ Polymer Overlay	Epoxy-Coated	1989	2006	2015/ 2016
C-760	None/ None	Epoxy-Coated	1989	NA	2005/ 2015
C-794	Polymer Overlay	Epoxy-Coated	1996	2003	2016
C-844	None	Epoxy-Coated	2001	NA	2005
C-919	None	Epoxy-Coated	2003	NA	2005
C-931	Polymer Overlay	Epoxy-Coated	2004	2004	2016
C-953	Polymer Overlay	Epoxy-Coated	2007	2007	2016
C-1035	None	Epoxy-Coated	2017	NA	2017
C-1036	None	Epoxy-Coated	2017	NA	2017
F-205	Asphalt Overlay	Uncoated	1978	1978	2011
F-330	Polymer Overlay	Uncoated	1974	1974	2014
F-402	Polymer Overlay	Uncoated	1980	2014	2017
F-403	Polymer Overlay	Epoxy-Coated	1980	2014	2017

Table 3-1: Bridge Deck Data (Continued)

Bridge ID	Surface Treatment Type	Reinforcement Type	Year of Deck Construction	Year of Surface Treatment Application	Year of Testing
F-439	Polymer Overlay	Epoxy-Coated	1983	2007	2017
F-476	Asphalt Overlay	Epoxy-Coated	1983	1995	2016
F-494	Polymer Overlay	Epoxy-Coated	1985	2007	2017
F-495	Polymer Overlay	Epoxy-Coated	1985	2007	2017
F-500	None	Epoxy-Coated	1984	NA	2016
F-504	None	Epoxy-Coated	1984	NA	2005
F-506	None	Epoxy-Coated	1985	NA	2005
F-53	Asphalt Overlay	Epoxy-Coated	2001	2001	2017
F-562	None	Epoxy-Coated	1989	NA	2016
F-738	Polymer Overlay	Epoxy-Coated	2008	2010	2016
F-799 (NB)	None/ None/ None/ None	Epoxy-Coated	2013	NA	2014/ 2015/ 2016/ 2017
F-799 (SB)	None/ None/ None/ None	Epoxy-Coated	2013	NA	2014/ 2015/ 2016/ 2017
F-800 (NB)	None/ None/ None/ None	Epoxy-Coated	2013	NA	2014/ 2015/ 2016/ 2017
F-800 (SB)	None/ None/ None/ None	Epoxy-Coated	2013	NA	2014/ 2015/ 2016/ 2017
F-862	None	Epoxy-Coated	2017	NA	2017
F-866	None	Epoxy-Coated	2017	NA	2017

3.2 Field Data Collection

On each of the 48 bridge decks, a minimum of four locations were randomly selected within the given lane(s) that was specified by UDOT for testing, for a total of 526 test locations. As shown in Figure 3-2, which displays a typical random sampling plan for both the longitudinal and transverse directions, the test locations generally included a main lane(s) and the adjacent

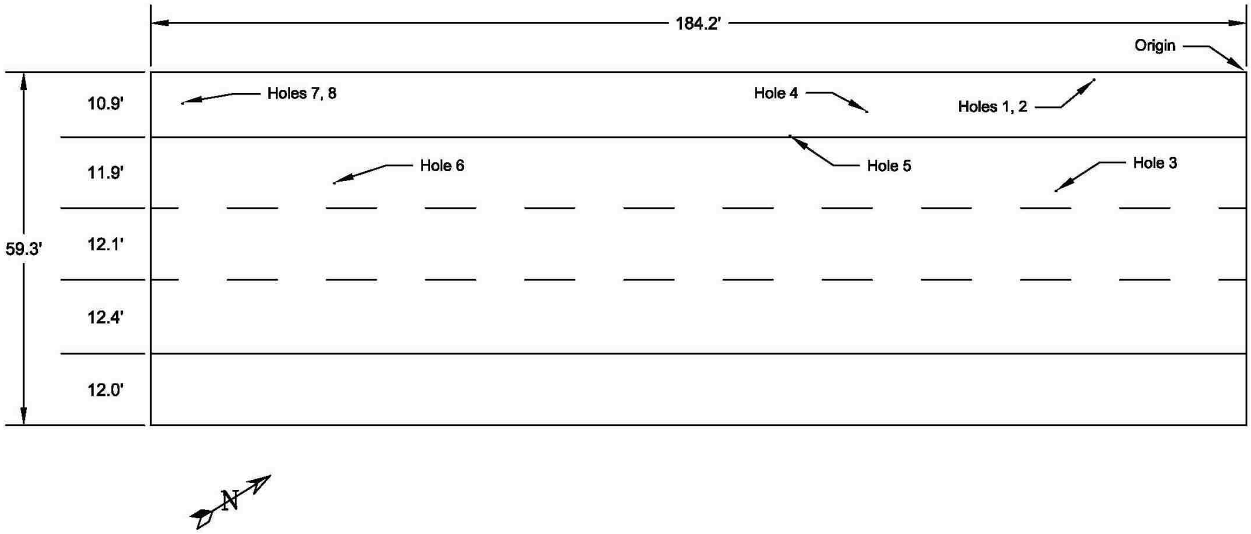

Figure 3-2: Typical random sampling plan for concrete bridge deck testing.

shoulder(s). At each test location, several tests were performed, including delamination surveys, cover depth measurements, and chloride concentration tests as explained in the following sections.

3.2.1 Delamination Surveys

Chain dragging and hammer sounding were performed to investigate the presence of delamination at each test location. Sounding procedures were performed in general accordance with American Society for Testing and Materials (ASTM) D 4580 (Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding). During chain dragging, which is depicted in Figure 3-3, a steel chain was dragged several times across the deck surface at each test location, and, in most cases, at least two researchers simultaneously listened to the acoustic response. For both chain dragging and hammer sounding, intact concrete was

Figure 3-3: Chain dragging.

characterized by a clear ringing sound, while delaminated concrete produced a dull, hollow sound (Sun 2017).

The presence of an overlay can yield misleading results when sounding methods are used to detect delaminations on concrete bridge decks. Especially on decks with polymer overlays, the operator may have difficulty determining if the change in acoustic response is the result of a delamination in the concrete or instead a separation of the overlay from the underlying concrete surface. Because of this issue, sounding was not performed on five of the 20 decks with polymer overlays.

3.2.2 Cover Depth Measurements

In this testing, researchers utilized a cover meter to determine the concrete cover depth at each test location, as shown in Figure 3-4. A cover meter is an instrument that uses pulse-

Figure 3-4: Cover depth measurements.

induction to locate the steel reinforcement embedded in the concrete and accurately measure the concrete cover depth when the rebar size has been entered (Sivasubramanian et. al 2013). Cover depth measurements were generally obtained above two adjacent longitudinal and two adjacent transverse bars at each test location.

3.2.3 Chloride Concentration Tests

A total of 1,857 concrete powder samples were collected for chloride concentration testing in this research. Drilling was performed to a maximum depth ranging from 1.0 in. to 8.0 in., with the variation in depths depending on whether drilling was performed between or above reinforcing bars and the maximum drilling depth permitted by UDOT on the given bridge deck. A rotary hammer was used to pulverize the concrete in 0.5-in. to 1.0-in. depth intervals, or lifts. The bit size was decreased with each lift to eliminate contamination of deeper samples that may have otherwise resulted from scraping of the bit against the inside of the hole at depths of shallower lifts during drilling. After the pulverized concrete from each lift was manually removed from the hole and placed in a bag, as shown in Figure 3-5, the hole and all tools were cleaned with a vacuum and/or compressed air before the next lift was drilled. Following sample collection, the hole was generally patched using an air-entrained, non-shrink grout, and the pulverized concrete was delivered to the BYU Highway Materials Laboratory for chloride concentration testing. The chloride concentration of each concrete sample in units of pounds of chloride per cubic yard of concrete was then determined in general accordance with ASTM

Figure 3-5: Concrete sampling for chloride concentration analysis.

C1152 (Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete), assuming a concrete density of 145 or 150 lb per cubic foot, depending on the bridge deck.

3.3 Data Compilation and Analysis

The data obtained from the delamination surveys, cover depth measurements, and chloride concentration testing were compiled and analyzed to address the objectives of this research. The tested bridge decks were divided into three surface treatment categories: 1) bare concrete, including concrete overlays, 2) polymer overlays, including thin-bonded epoxy and healer/sealer applications, and 3) asphalt overlays. The latter two categories were further divided by treatment time, which was important, for example, because an overlay applied soon after construction of a bridge deck could have significantly different effects on deck deterioration rates than would be expected for an overlay applied many years later. Specific ranges in deck age at the time of treatment were determined after analysis of the available data.

Among the 526 test locations, 494 were drilled between bars in the top mat of reinforcing steel, and 32 were drilled directly above bars in the top mat of reinforcing steel. In every case, the location at which drilling was performed directly above a bar was within about 4 in. of a separate location at which drilling was performed between bars. For analyses related to the first objective of this research, the data from only the 494 test locations between bars were used. For analyses related to the second objective of this research, the data from the 32 test locations directly above bar and the corresponding 32 test locations between bars were used.

3.4 Summary

The BYU Materials and Pavements Research Group performed testing of 48 concrete bridge decks in Utah between the years 2004 and 2017. On each of the 48 bridge decks, a minimum of four locations were randomly selected within the given lane(s) that was specified by UDOT for testing, for a total of 526 test locations. Chain dragging and hammer sounding were performed to investigate the presence of delamination at each test location. In addition to performing delamination surveys, researchers utilized a cover meter to determine the concrete cover depth. A total of 1,857 concrete powder samples were collected for chloride concentration testing in this research. The data obtained from the delamination surveys, cover depth measurements, and chloride concentration testing were compiled and analyzed to address the objectives of this research.

4 RESULTS

4.1 Overview

The results of this research are based on two to eight chloride concentration samples extracted from each of 526 test locations on 48 bridge decks at which cover depth measurements and sounding were also performed. The compiled data are presented in the appendix. Several limitations apply to the research findings. Because the chloride concentration data were compiled from numerous, independent projects previously performed by the BYU Materials and Pavements Research Group between the years 2004 and 2017, the data structure is not governed by an overarching experimental design. That is, because the results analyzed in this research were developed from a sample of convenience rather than a controlled experiment, not all factors that may have potentially influenced the results were documented, measured, or accounted for in the analyses. Instead, the data set is incomplete and unbalanced in some aspects pertaining to the objectives of the current efforts. Furthermore, because random sampling from defined populations was not possible in this research, the results may not be generally applicable to the populations; the results are most applicable to bridges with similar design, construction, materials, trafficking, environmental conditions, and maintenance practices as those included in this study. Characterization of typical bridge criteria, analysis of relationships between bridge deck characteristics, determination of phase durations, and comparisons of chloride concentrations for samples extracted between bar and above bar are discussed in the following sections.

4.2 Bridge Deck Characterization

The concrete bridge decks included in this research were characterized by cover depth and deck age. The frequency distributions of cover depth and deck age for the tested decks are presented in Figures 4-1 and 4-2, respectively. The distributions show the typical ranges of these deck properties as determined at the time of deck testing for the three different surface types, including bare concrete, polymer overlay, and asphalt overlay, that were represented in the study. (For each bin in the figures, the lower limit is inclusive, while the upper limit is exclusive.)

Regarding cover depth, data were available for a total of 460 test locations on 48 bridge decks at which cover depth measurements had been obtained. Figure 4-1 shows that the majority

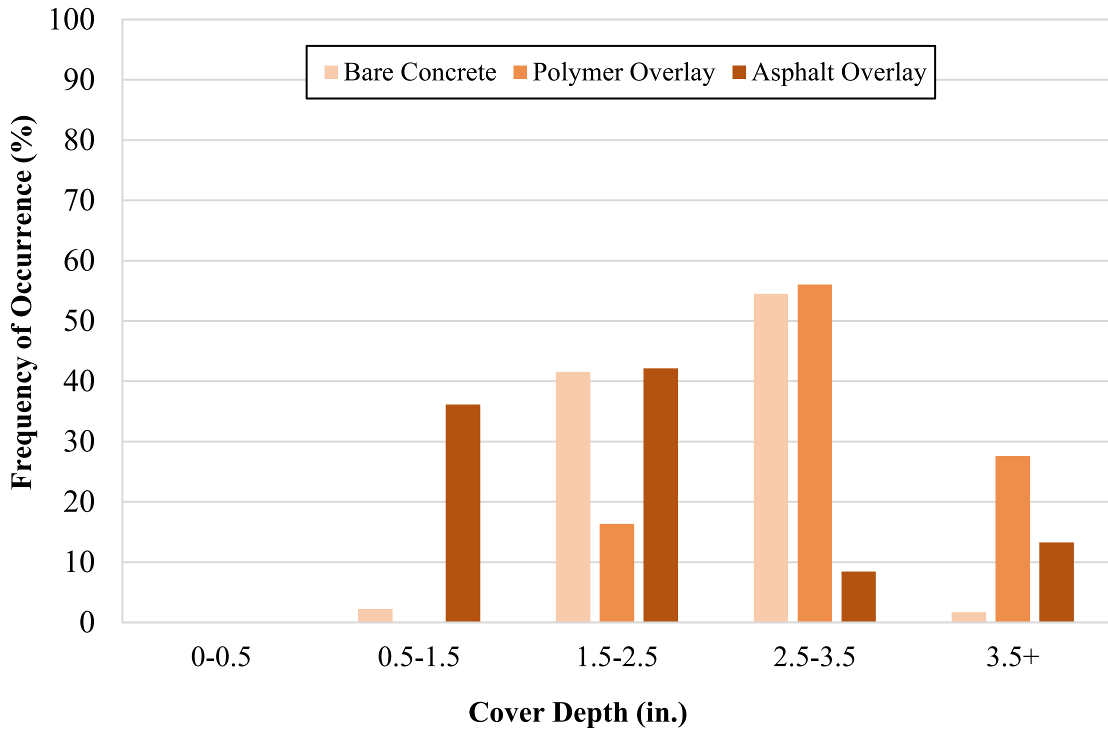

Figure 4-1: Frequency distribution for cover depth.

of the measured cover depths ranged from 1.5 to 3.5 in., with a typical cover depth of approximately 2.5 in.

Regarding deck age, data were available for all 48 bridge decks included in this research. Figure 4-2 shows that the majority of decks tested with polymer and asphalt overlays were older than 20 years of age at the time of testing, while the majority of bare concrete decks were either less than 5 years or greater than 20 years in age. Regardless of surface type, comparatively few of the tested decks were 5 to 20 years in age; the lower number of decks in this age range is likely attributable to the apparent focus of the previous research studies on older decks that were exhibiting deterioration or newer decks that were constructed using new methods or materials for which early-age evaluations were desired.

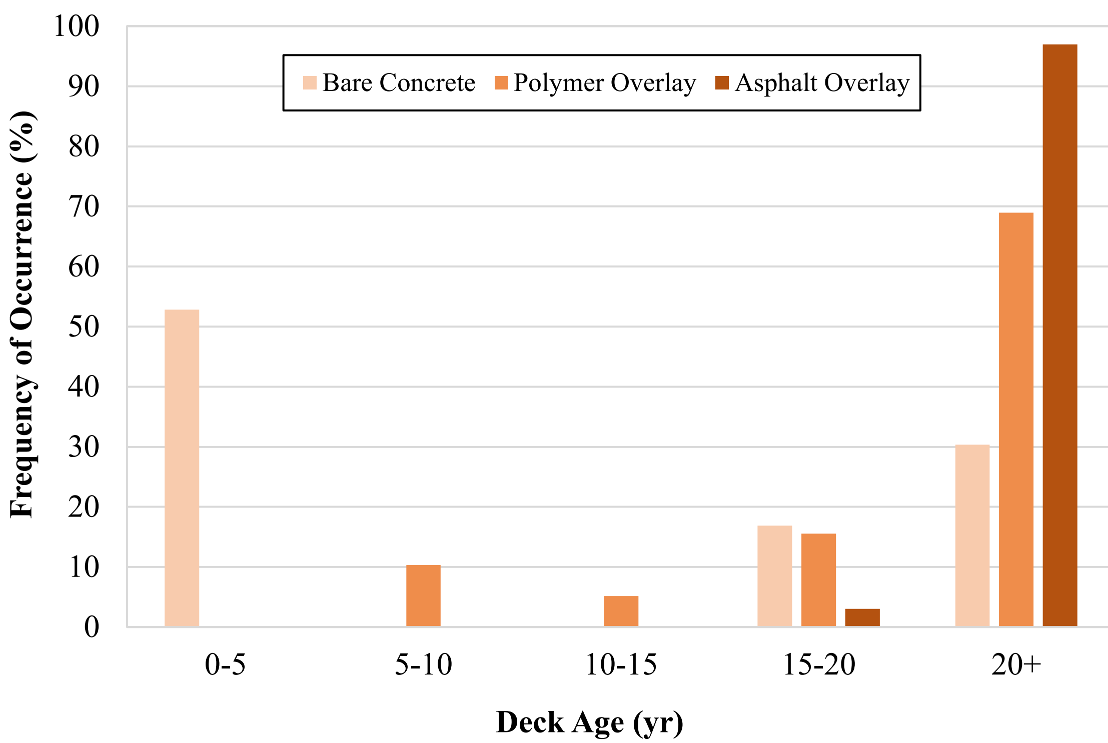

Figure 4-2: Frequency distribution for deck age.

4.3 Data Compilation and Analysis

The data collected from the 48 concrete bridge decks included in this research were used to address both of the objectives stated for this research. The first research objective involved investigating relationships among chloride concentration at the top mat of reinforcing steel, deck age, cover depth, and occurrence of delamination for concrete bridge decks with selected surface treatments and rebar types to help establish a greater understanding about the duration of each phase of the deterioration process. The second research objective involved investigating the relationship between chloride concentrations that develop between the bars and those that develop directly above the bars in the top mat of reinforcing steel to better understand the effects of the presence of reinforcing steel on diffusion of chloride ions through the concrete matrix. Regarding the first objective, baseline relationships between chloride concentration, deck age, and cover depth were developed for bare concrete decks at depths ranging from 0.5 in. to 6.5 in., as shown in Figure 4-3. The data are based on test results obtained from a total of 44 test locations positioned between the bars in the top mat of reinforcing steel on a total of 24 bare concrete decks, all of which contained epoxy-coated reinforcement, and chloride concentrations at the indicated depths were determined through linear interpolation from the actual measurements. Figure 4-3 shows that, as deck age increases, chloride concentration also increases and that chloride concentrations are much higher for shallower concrete depths, such as 0.5 in. or 1.5 in., than for deeper concrete depths, such as 5.5 in. or 6.5 in., as expected. The regression lines in Figure 4-3 can be used to estimate the phase durations of a typical, bare concrete bridge deck in Utah. For example, for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth, the critical chloride threshold of 2.0 lb Cl^-/yd^3 of concrete is reached at approximately 4, 5, and 7 years, respectively, which would be the duration of the first phase of the deterioration

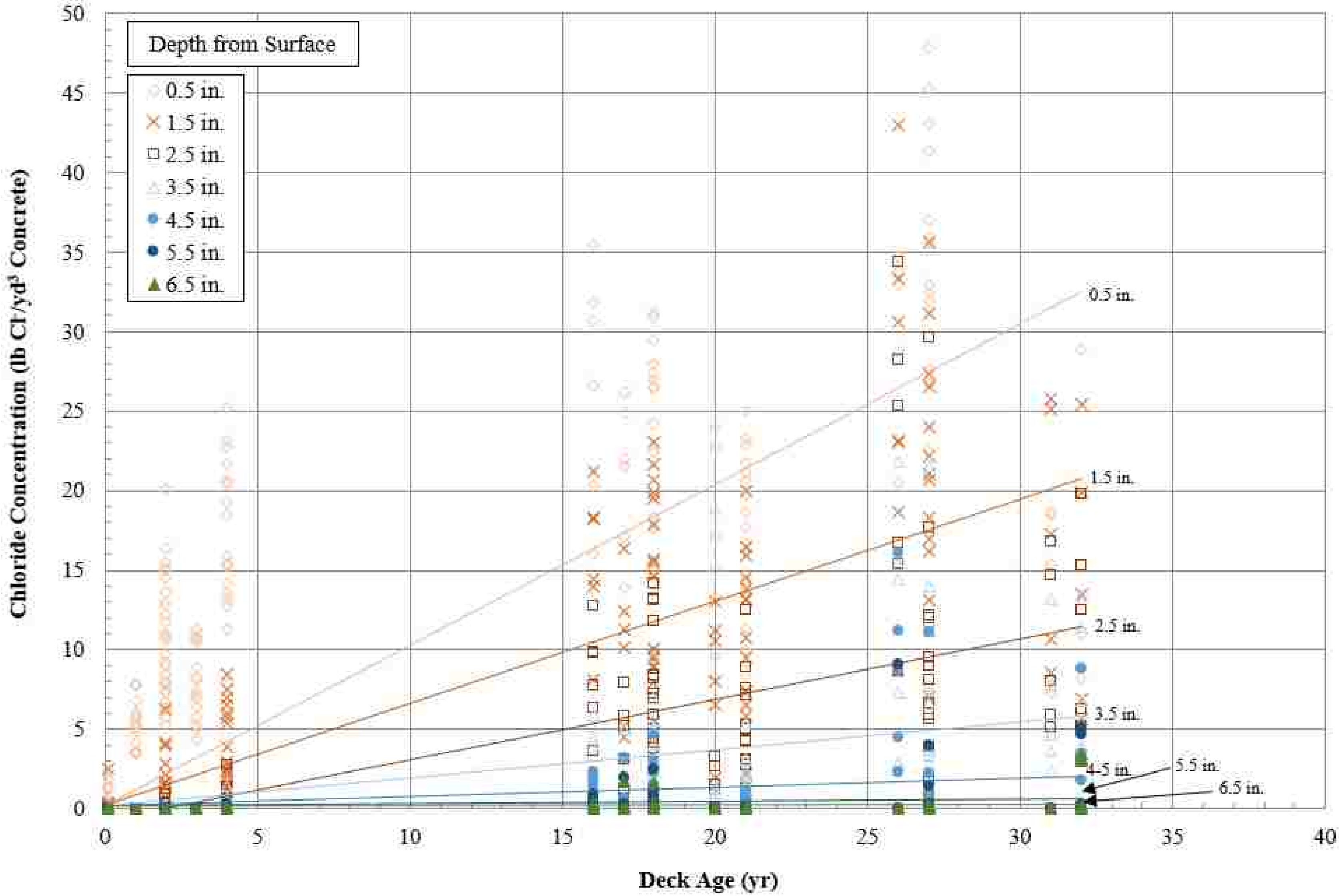

Figure 4-3: Relationship between chloride concentration at various concrete depths and deck age for bare concrete decks.

process described in Chapter 2. The *y*-intercept value of approximately 0.2 lb Cl^{-}/yd^3 of concrete for all of the regression lines is an estimate of the average base chloride content of the aggregates utilized for concrete production in Utah. These results are summarized in Table 4-1.

For decks with asphalt or polymer overlays, development of clear relationships between chloride concentration, deck age, and cover depth required consideration of treatment time as explained in Chapter 3; while figures such as Figure 4-3 could have been prepared for decks with asphalt or polymer overlays, clear relationships would not have been expected because an overlay applied soon after construction of a bridge deck could have significantly different effects on deck deterioration rates than would be expected for an overlay applied many years later. Therefore, relationships between chloride concentration and deck age were developed for

Table 4-1: Duration of First Phase of Deterioration Process by Surface Treatment Type and Timing and Cover Depth

Surface Treatment Type and Timing	Duration of First Phase of Deterioration Process (yr)		
	2.0-in. Cover Depth	2.5-in. Cover Depth	3.0-in. Cover Depth
Bare Concrete	4	5	7
Asphalt Overlay Applied Immediately After Construction	33	38	41
Asphalt Overlay Applied 1-10 Years After Construction	26	33	37
Asphalt Overlay Applied 10+ Years After Construction	5	6	7
Polymer Overlay Applied Immediately After Construction	13	18	21
Polymer Overlay Applied 5-10 Years After Construction	8	11	15
Polymer Overlay Applied 10-15 Years After Construction	5	7	11
Polymer Overlay Applied 15+ Years After Construction	4.5	6	8

specific ranges in deck age at the time of treatment and are presented for common cover depths of 2.0 in., 2.5 in., and 3.0 in.

Figures 4-4, 4-5, and 4-6 present the relationships developed for decks with asphalt overlays. The data are based on test results obtained from a total of 157 test locations positioned between the bars in the top mat of reinforcing steel on a total of eight decks, five of which contained epoxy-coated reinforcement, and chloride concentrations at the indicated depths were determined through linear interpolation from the actual measurements. The data in each figure are divided into groups representing three different treatment times, including immediately after construction, 1 to 10 years after construction, and 10 or more years after construction, with sample sizes of three, two, and three decks, respectively. (For each age range in the figures, the lower limit is inclusive, while the upper limit is exclusive.) Because both of the decks in the treatment time category of 1 to 10 years after construction were tested at exactly the same age, 47 years, a true regression line could not be developed for this category; however, assuming a *y*-intercept value of 0.2 lb Cl^-/yd^3 of concrete enabled development of a regression line that allows a visual comparison of the three different treatment times. Figures 4-4, 4-5, and 4-6 again show that, as deck age increases, chloride concentration also increases. The figures also show that chloride concentration decreases as cover depth increases from 2.0 in. to 3.0 in. Chloride concentrations for decks that had an asphalt overlay applied 10 or more years after construction are higher than those for decks with an asphalt overlay applied immediately after construction. Regarding the duration of the first phase of the deterioration process, the critical chloride threshold of 2.0 lb Cl^-/yd^3 of concrete for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had an asphalt overlay applied immediately after construction is reached at approximately 33, 38, and 40 years, respectively. Comparatively, the critical chloride threshold for decks with 2.0-in.,

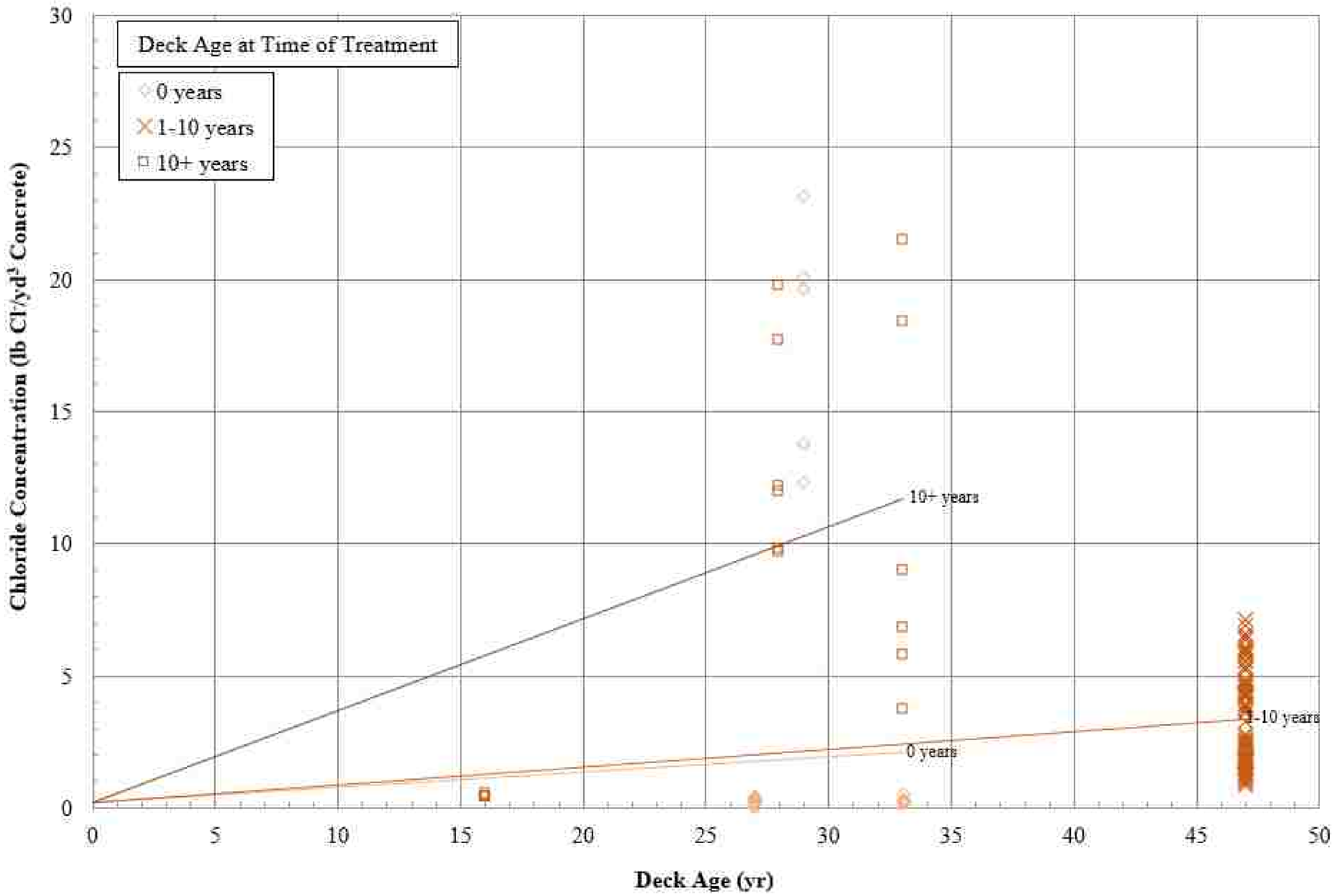

Figure 4-4: Relationship between chloride concentration at 2.0-in. concrete depth and deck age for decks with asphalt overlays applied at indicated time of treatment.

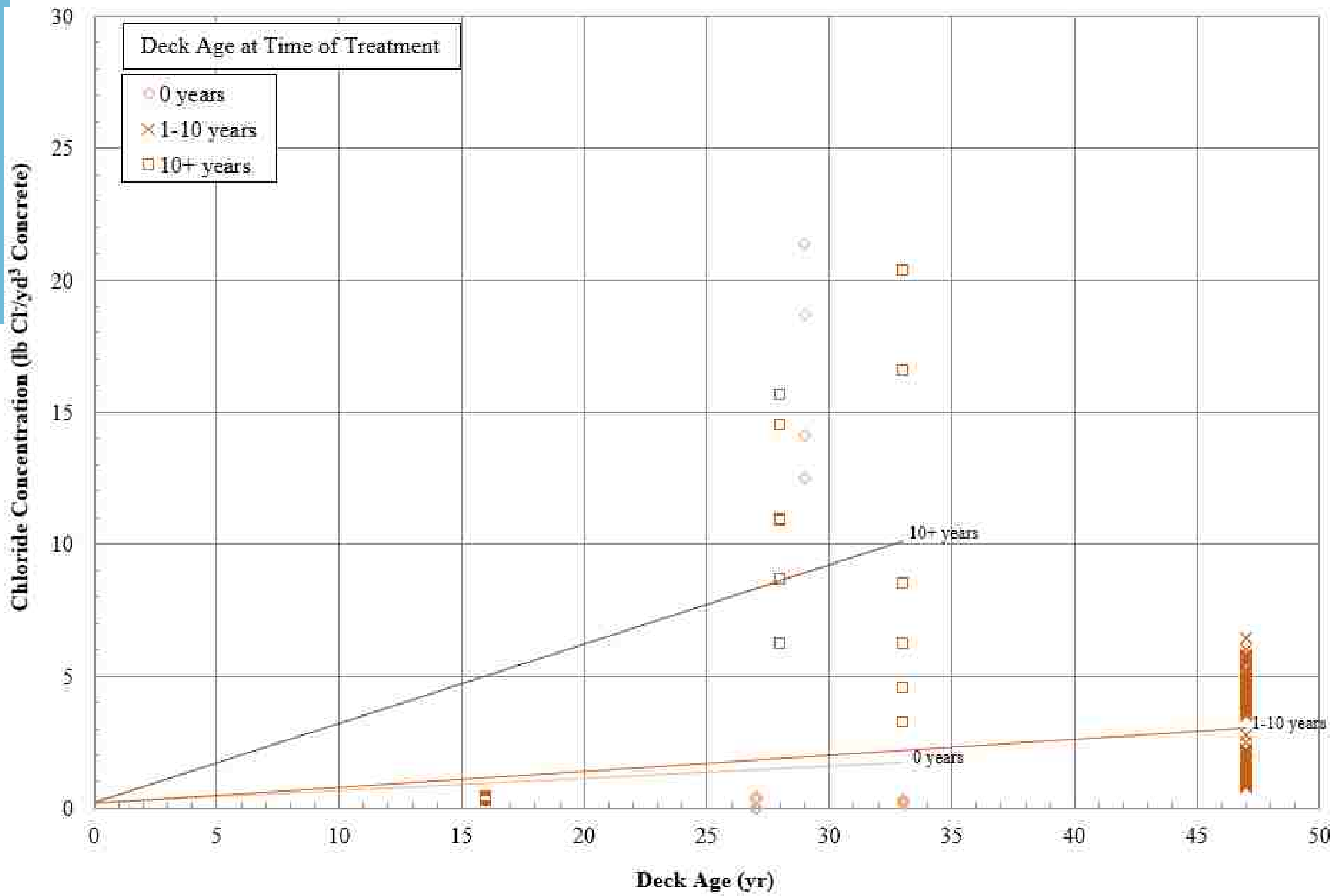

Figure 4-5: Relationship between chloride concentration at 2.5-in. concrete depth and deck age for decks with asphalt overlays applied at indicated time of treatment.

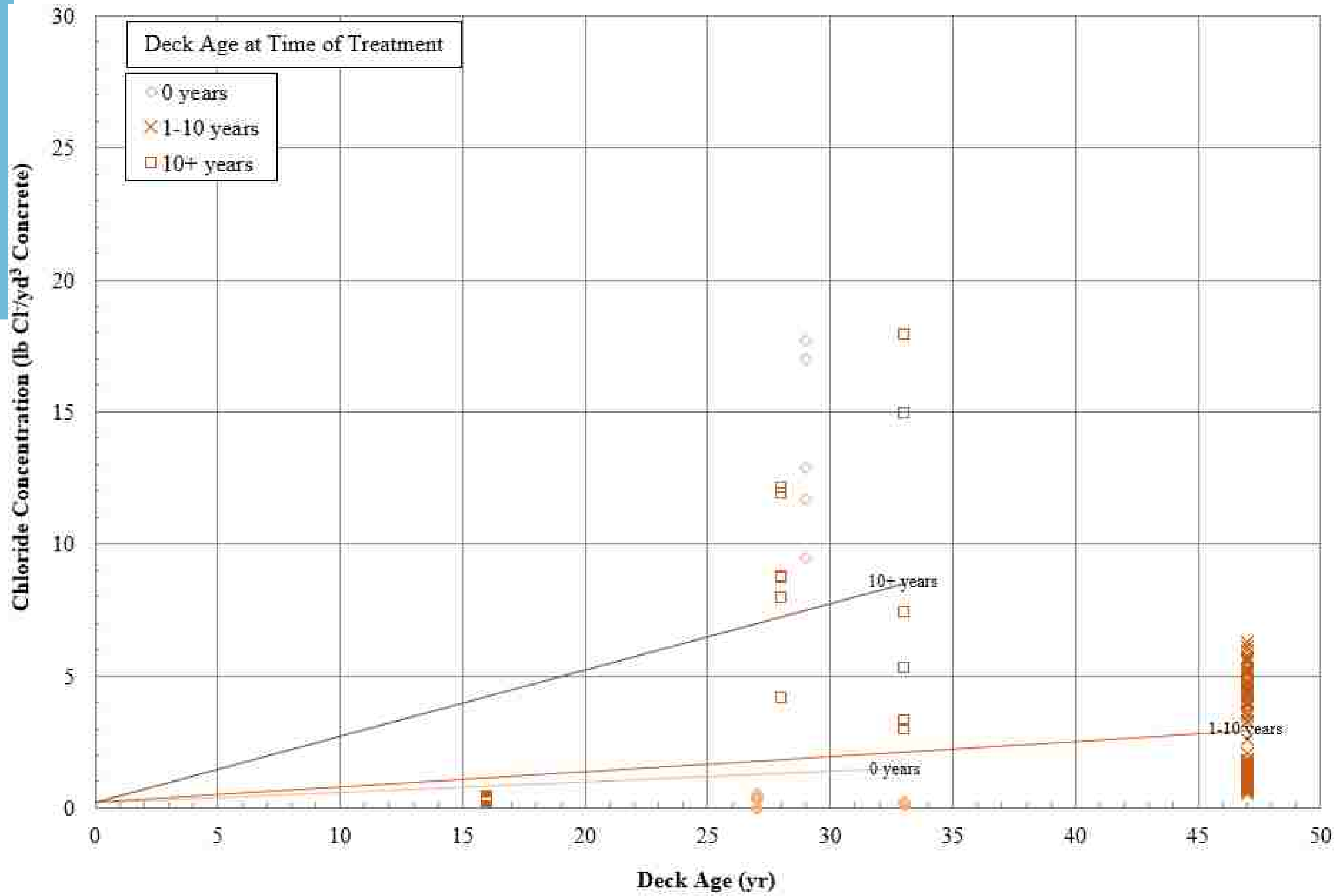

Figure 4-6: Relationship between chloride concentration at 3.0-in. concrete depth and deck age for decks with asphalt overlays applied at indicated time of treatment.

2.5-in., and 3.0-in. cover depth that had an asphalt overlay applied 1 to 10 years after construction is reached at approximately 26, 33, and 40 years, respectively. Finally, the critical chloride threshold for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had an asphalt overlay applied 10 or more years after construction is reached at approximately 5, 6, and 7 years, respectively. These results, which are summarized in Table 4-1, indicate that the deterioration process can be substantially delayed when an asphalt overlay is applied immediately or soon after construction.

Figures 4-7, 4-8, and 4-9 present the relationships developed for decks with polymer overlays. The data are based on test results obtained from a total of 117 test locations positioned between the bars in the top mat of reinforcing steel on a total of 19 decks, 14 of which contained epoxy-coated reinforcement, and chloride concentrations at the indicated depths were determined through linear interpolation from the actual measurements. The data in each figure are divided into groups representing five different treatment times, including immediately after construction, 1 to 5 years after construction, 5 to 10 years after construction, 10 to 15 years after construction, and 15 or more years after construction, with sample sizes of seven, zero, three, four, and six decks, respectively. (Again, for each age range in the figures, the lower limit is inclusive, while the upper limit is exclusive.) Because there were no decks in the treatment time category of 1 to 5 years after construction, a regression line could not be developed for that category. Figures 4-7, 4-8, and 4-9 again show that, as deck age increases, chloride concentration also increases. The figures also show that chloride concentration decreases as cover depth increases from 2.0 in. to 3.0 in. Chloride concentrations for decks that had a polymer overlay applied 15 or more years after construction are higher than those for decks with a polymer overlay applied immediately after construction. Regarding the duration of the first phase of the deterioration process, the

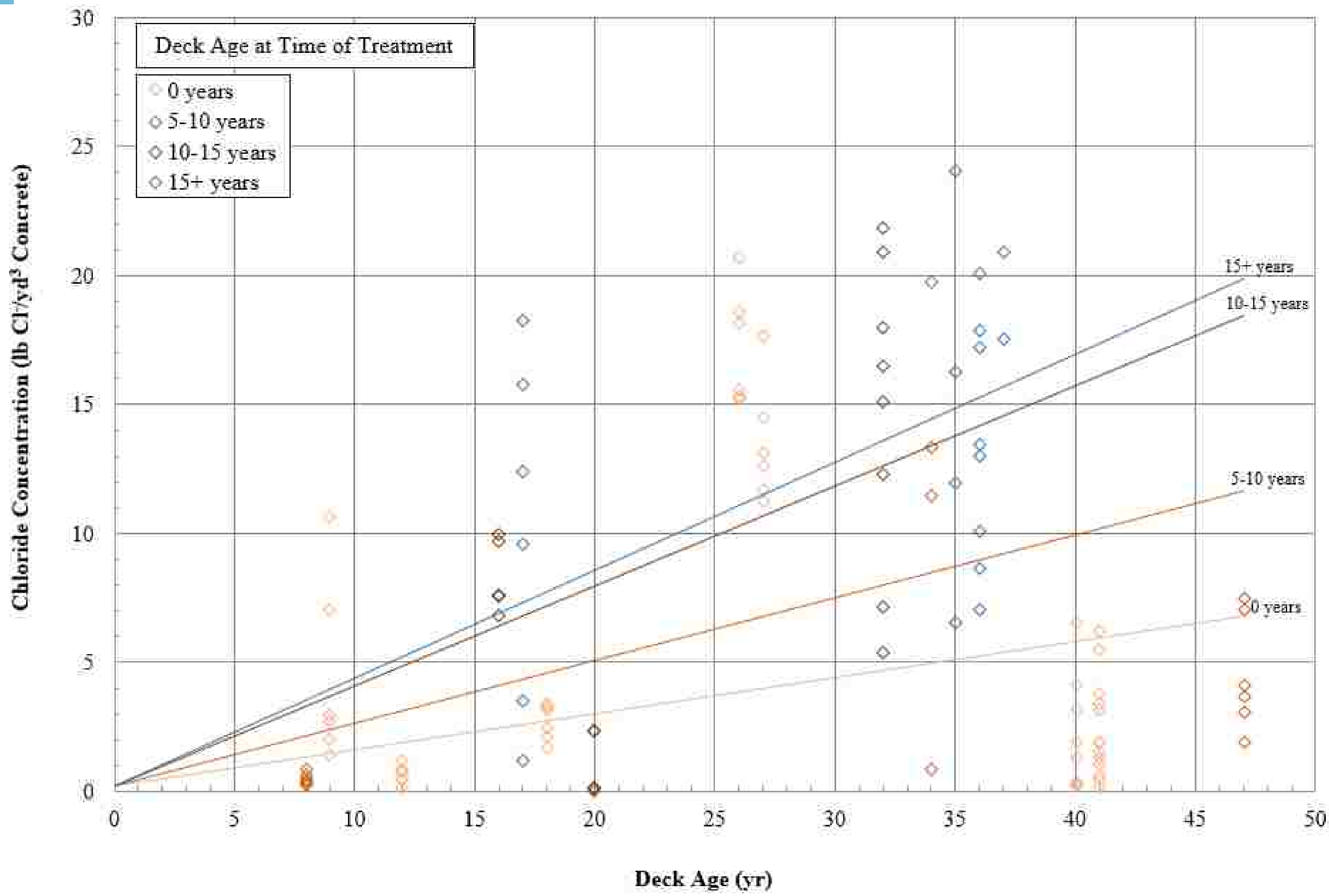

Figure 4-7: Relationship between chloride concentration at 2.0-in. concrete depth and deck age for decks with polymer overlays applied at indicated time of treatment.

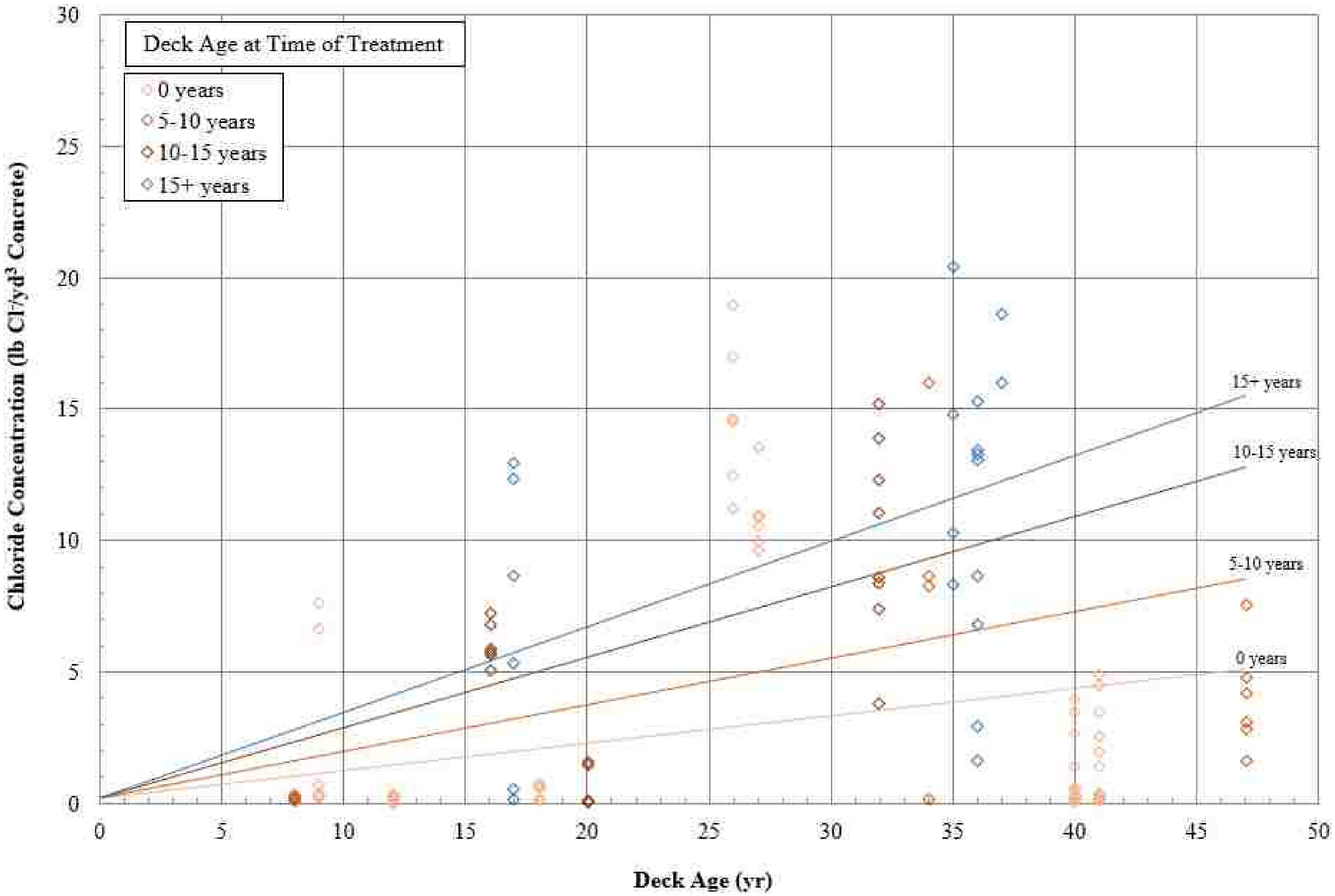

Figure 4-8: Relationship between chloride concentration at 2.5-in. concrete depth and deck age for decks with polymer overlays applied at indicated time of treatment.

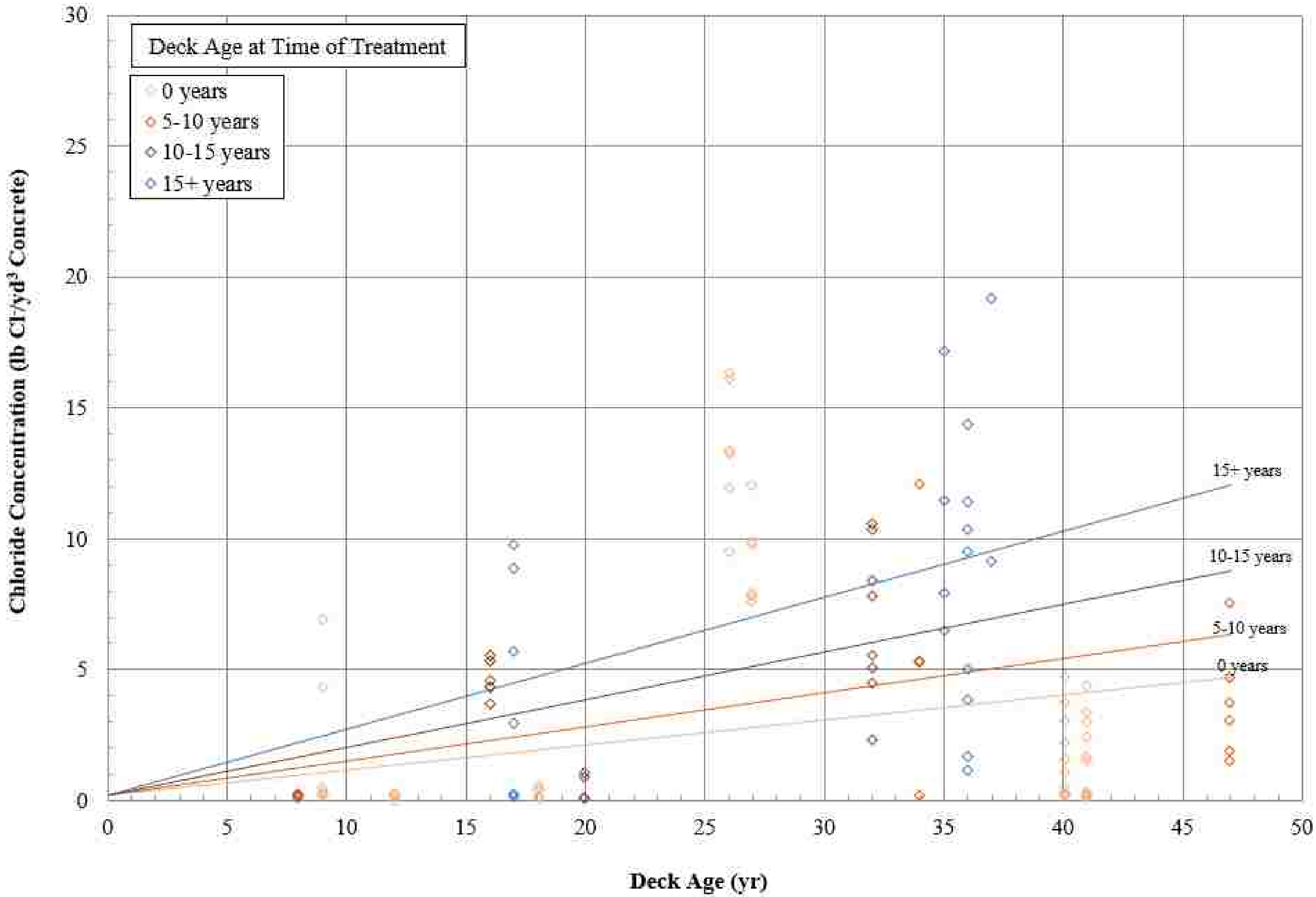

Figure 4-9: Relationship between chloride concentration at 3.0-in. concrete depth and deck age for decks with polymer overlays applied at indicated time of treatment.

critical chloride threshold of 2.0 lb Cl^-/yd^3 of concrete for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had a polymer overlay applied immediately after construction is reached at approximately 13, 18, and 21 years, respectively. Comparatively, the critical chloride threshold for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had a polymer overlay applied 5 to 10 years after construction is reached at approximately 8, 11, and 15 years, respectively. The critical chloride threshold for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had a polymer overlay applied 10 to 15 years after construction is reached at approximately 5, 7, and 11 years, respectively. Finally, the critical chloride threshold for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had a polymer overlay applied 15 or more years after construction is reached at approximately 4.5, 6, and 8 years, respectively. These results, which are summarized in Table 4-1, indicate that the deterioration process can be substantially delayed when a polymer overlay is applied immediately or soon after construction.

Following analysis of the individual deck types, the relationships between chloride concentration and deck age were compared for all three deck types for two different treatment times. For cover depths of 2.0 in., 2.5 in., and 3.0 in., respectively, Figures 4-10, 4-11, and 4-12 compare the results for bare decks with those for decks that received asphalt or polymer overlays immediately after construction, while Figures 4-13, 4-14, and 4-15 compare the results for bare decks with those for decks that received asphalt or polymer overlays 10 or more years after construction. The data in these figures clearly show the benefits of applying surface treatments immediately or soon after construction. For example, Figure 4-11 indicates that, for a 2.5-in. cover depth and a deck age of 20 years, the chloride concentration is estimated to be 6.0 lb Cl^-/yd^3 of concrete for a bare concrete deck, 1.5 lb Cl^-/yd^3 of concrete for a deck with an asphalt overlay, and 2.8 lb Cl^-/yd^3 of concrete for a deck with a polymer overlay for the case when the

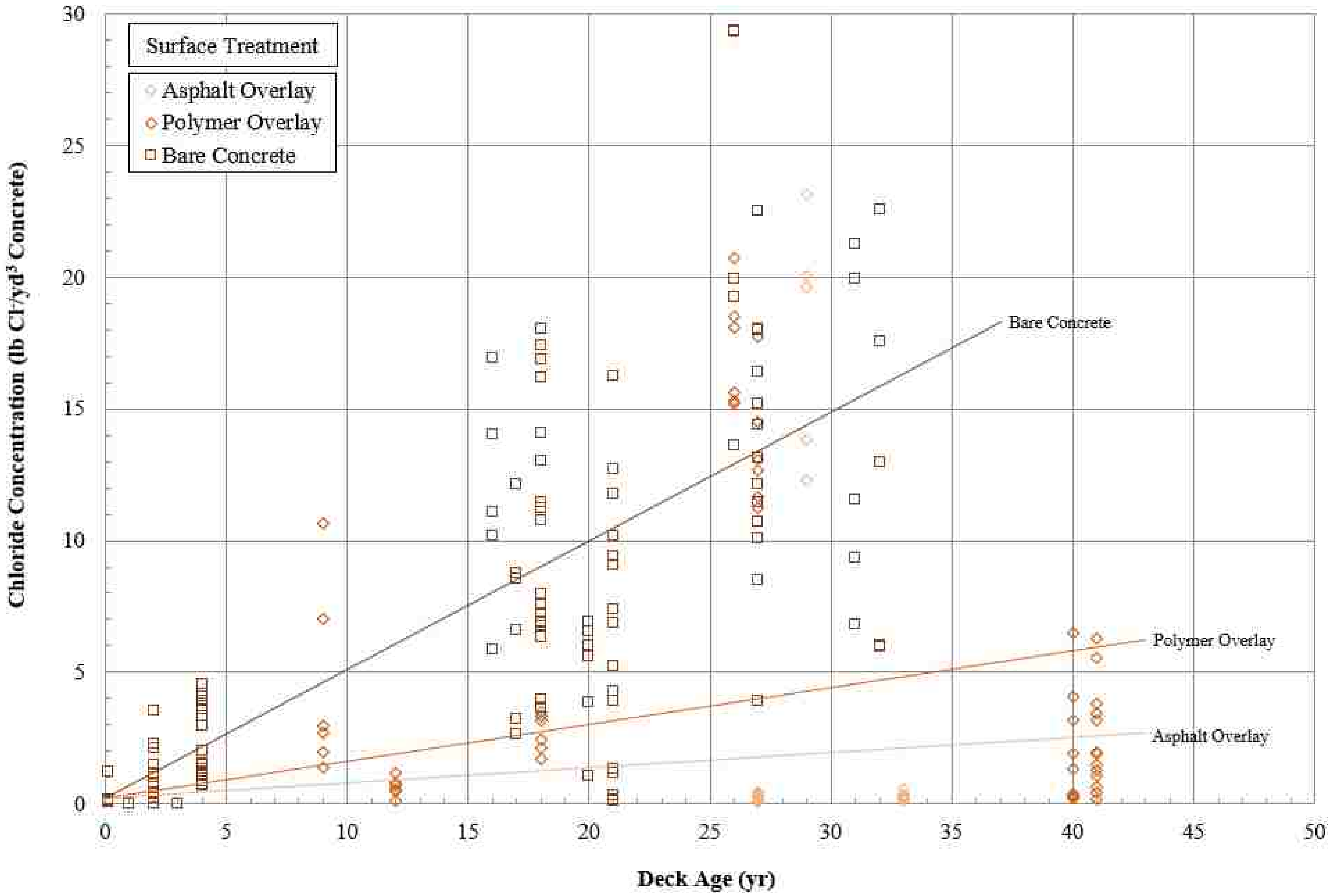

Figure 4-10: Relationship between chloride concentration at 2.0-in. concrete depth and deck age for decks with surface treatments that were applied immediately after construction.

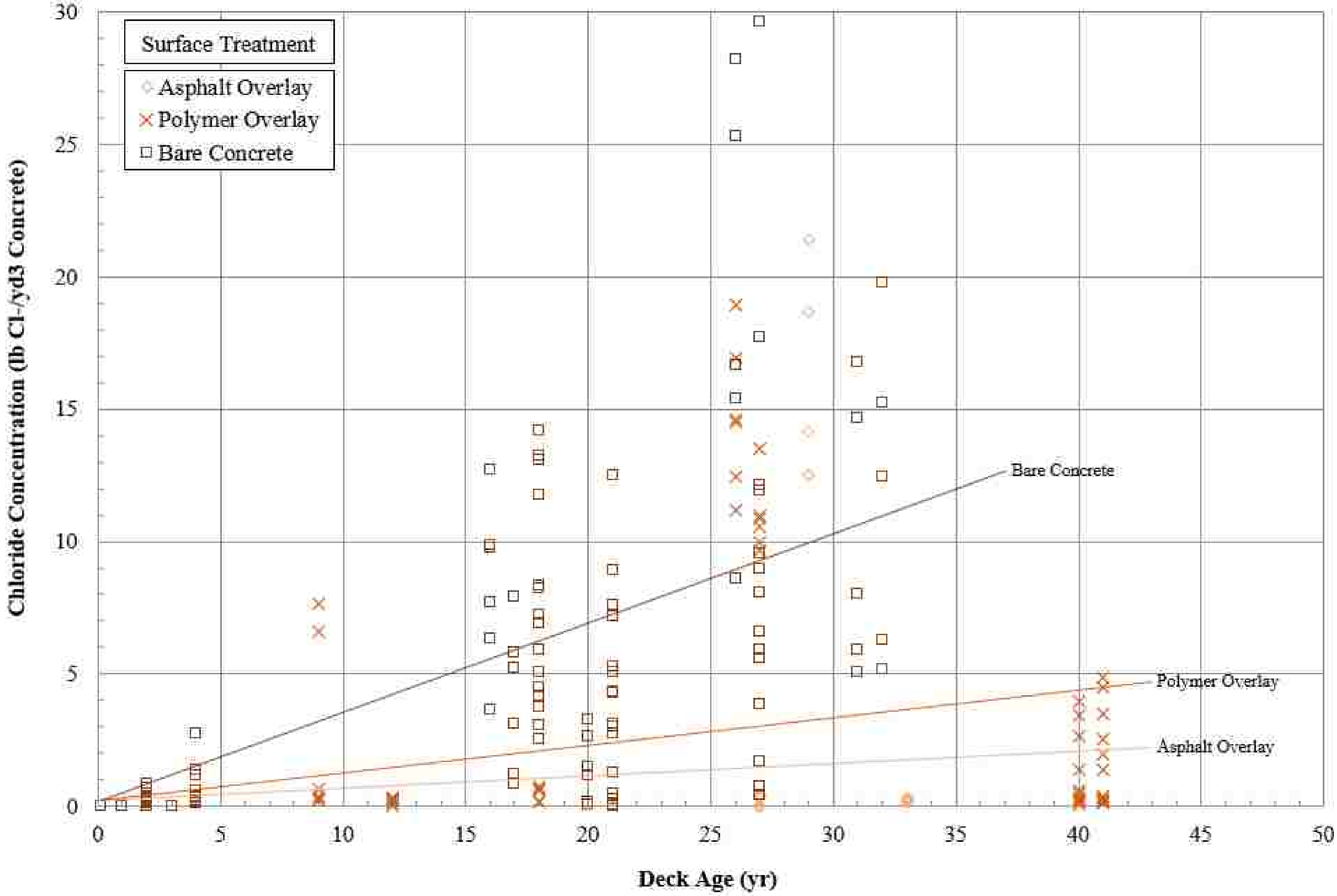

Figure 4-11: Relationship between chloride concentration at 2.5-in. concrete depth and deck age for decks with surface treatments that were applied immediately after construction.

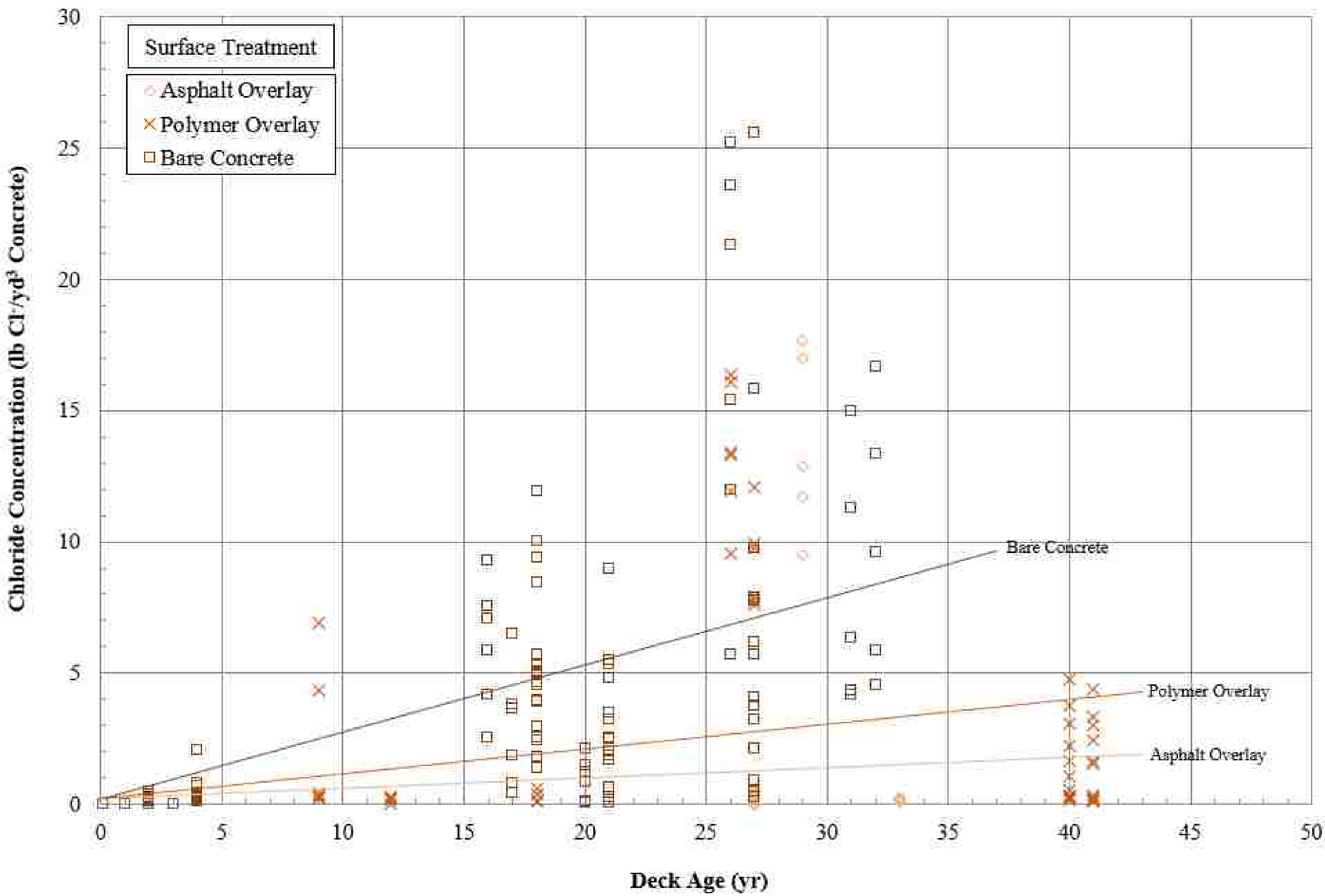

Figure 4-12: Relationship between chloride concentration at 3.0-in. concrete depth and deck age for decks with surface treatments that were applied immediately after construction.

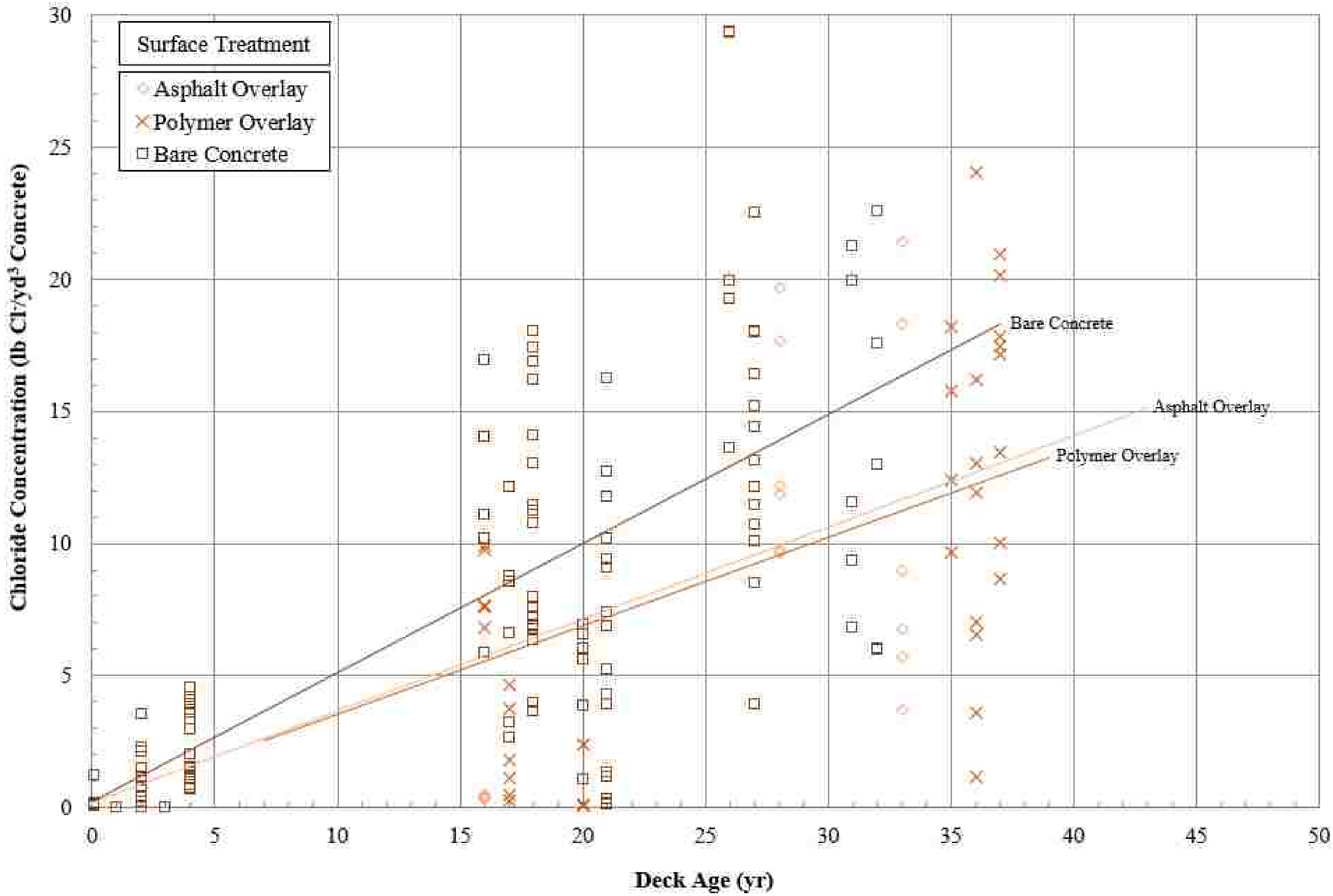

Figure 4-13: Relationship between chloride concentration at 2.0-in. concrete depth and deck age for decks with surface treatments that were applied 10 or more years after construction.

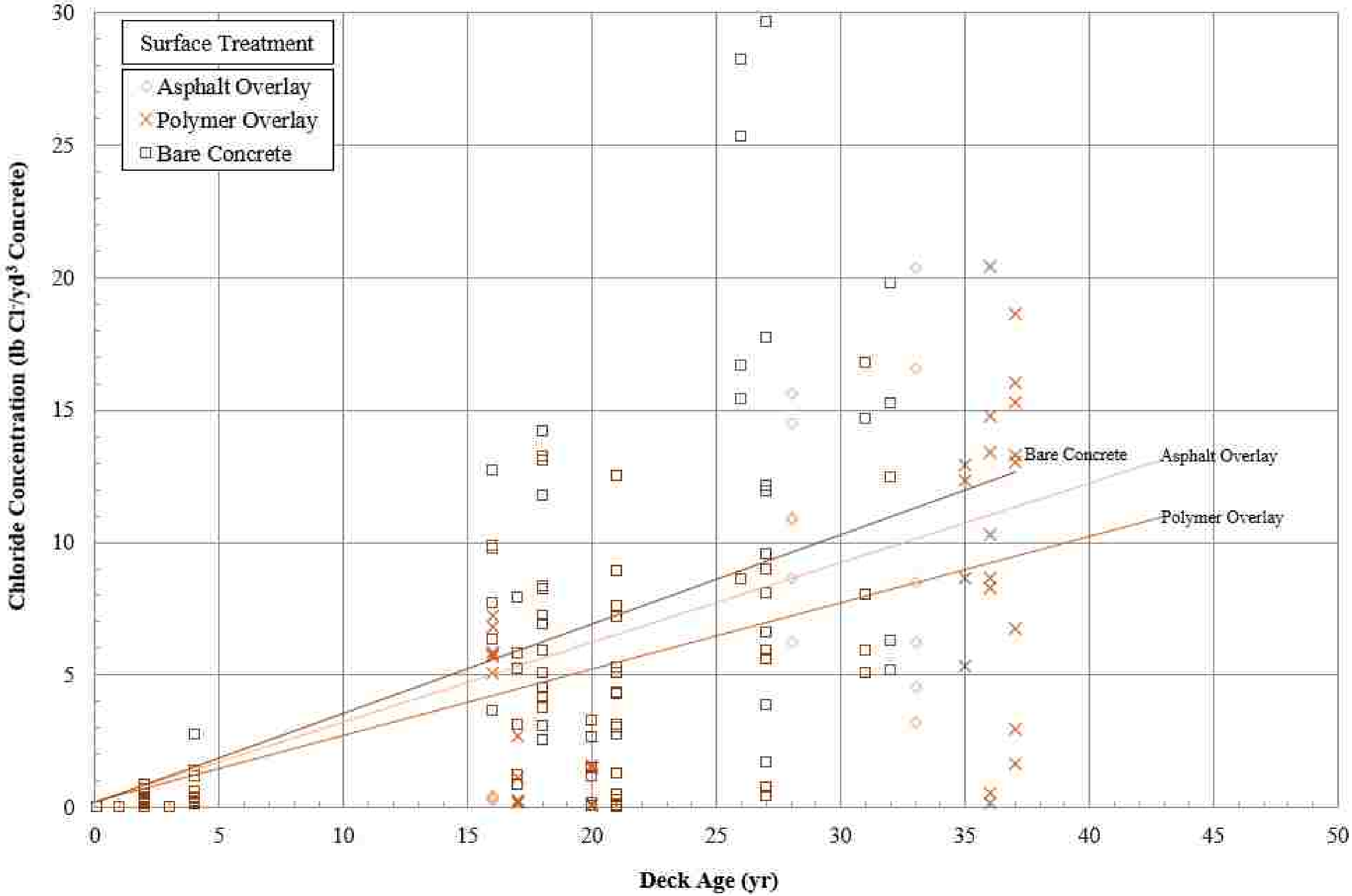

Figure 4-14: Relationship between chloride concentration at 2.5-in. concrete depth and deck age for decks with surface treatments that were applied 10 or more years after construction.

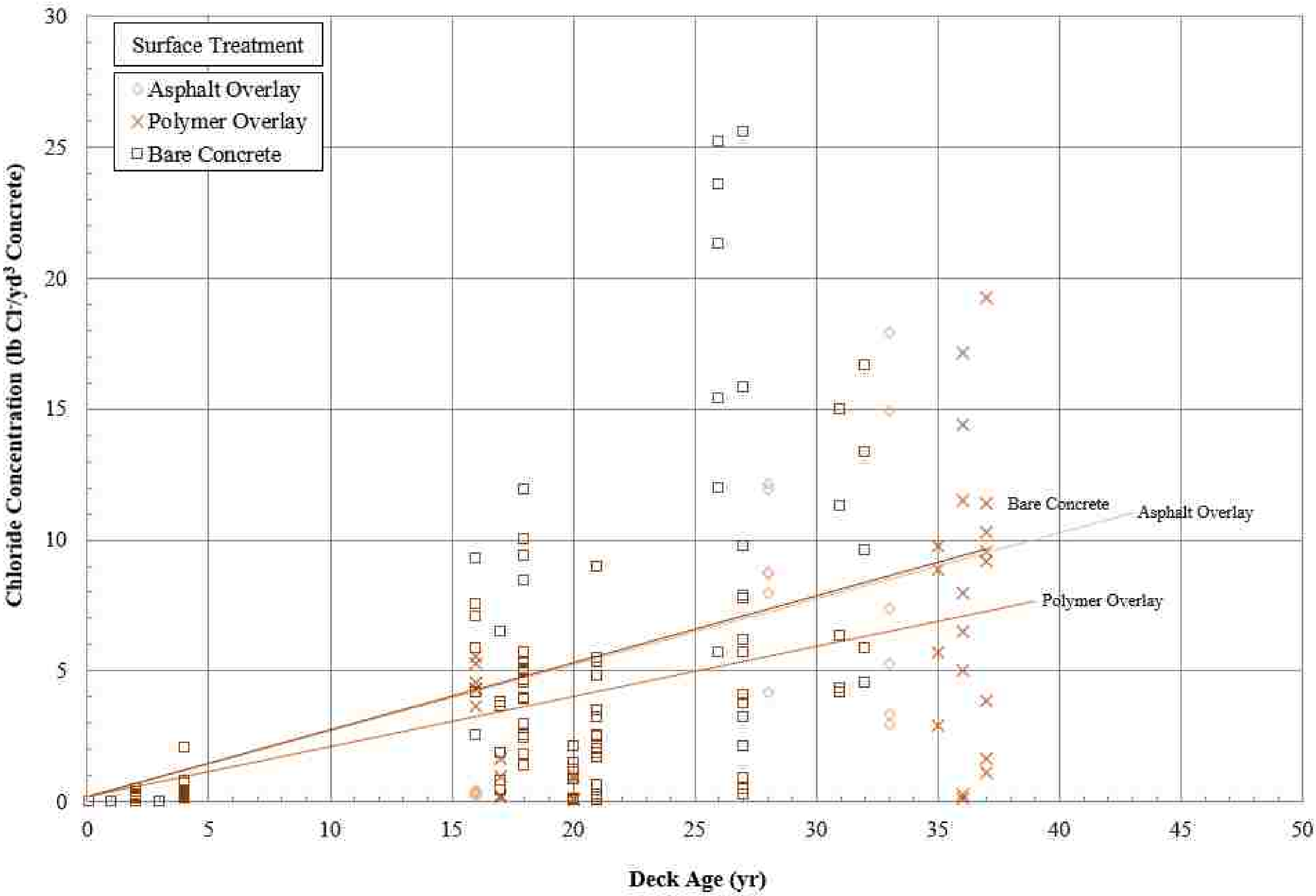

Figure 4-15: Relationship between chloride concentration at 3.0-in. concrete depth and deck age for decks with surface treatments that were applied 10 or more years after construction.

overlays are applied immediately after construction. For the case when the overlays are applied 10 or more years after construction, Figure 4-14 indicates that, for the same cover depth and deck age, the chloride concentration is estimated to be 6.5, 6.0, and 5.5 lb Cl^-/yd^3 of concrete for a bare concrete deck, a deck with an asphalt overlay, and a deck with a polymer overlay, respectively; minimal benefit from the overlays is observed in this case, as chlorides would have already penetrated the concrete cover by the time the overlay was applied. The data also suggest that asphalt overlays may be more effective than polymer overlays when applied immediately after construction, while polymer overlays may be more effective than asphalt overlays when applied 10 or more years after construction; further research would be needed to investigate this topic, as statistical analysis may show that the relationships presented in some of these cases are not significantly different.

Relevant to determining the duration of the second phase of the deterioration process, Figure 4-16 presents the relationship between delamination occurrence and chloride concentration for bare concrete bridge decks. The data, representing results obtained at 124 test locations on seven bridge decks with black bar and 203 test locations on 34 bridge decks with epoxy-coated bar for a total of 327 test locations on 41 bridge decks, have been grouped into four chloride concentration categories for analysis. For categories with chloride concentrations ranging from 0.0 to 2.0, 2.0 to 4.0, 4.0 to 6.0, and greater than 6.0 lb Cl^-/yd^3 of concrete, the samples sizes were 46, 37, 34, and 7 for bridge decks with black bar and 102, 12, 23, and 66 for bridge decks with epoxy-coated bar, respectively. (For each chloride concentration category, the lower limit is inclusive, while the upper limit is exclusive.) The chloride concentrations are those measured at the level of the top mat of reinforcing steel in all cases, and occurrence of delamination was determined from sounding at the time of chloride concentration sampling.

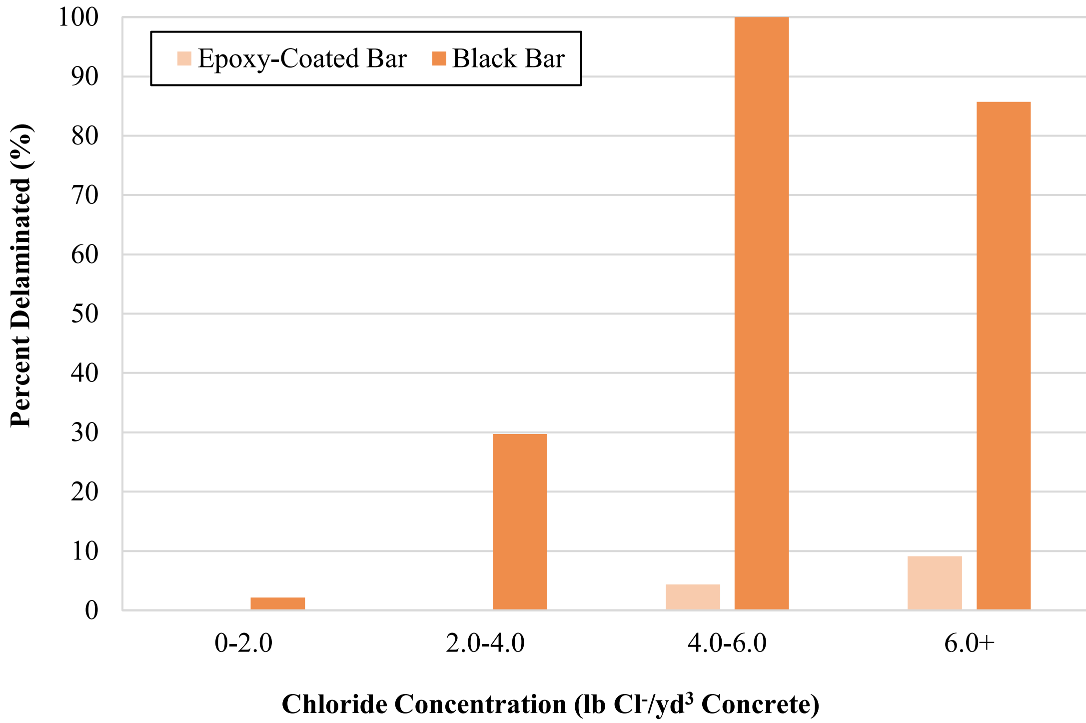

Figure 4-16: Chloride concentration and occurrence of delamination for concrete bridge decks with epoxy-coated bar and black bar.

Only bare decks and decks with overlays that could be removed before sounding were included in this analysis because of the difficulty associated with distinguishing delamination within a concrete deck from debonding of an overlay using sounding. In general, Figure 4-16 shows that the occurrence of delamination increases with increasing chloride concentration; the slight decrease in the percent delaminated value associated with black bar for chloride concentrations greater than 6.0 lb Cl^-/yd^3 of concrete compared to those ranging from 2.0 to 4.0 lb Cl^-/yd^3 of concrete may be a result of shallow patching repairs applied to previously delaminated areas in some cases.

For determining the duration of the second phase of the deterioration process, identifying an extent of deck damage that would initiate the third phase of the deterioration process was necessary. Based on the results of a national questionnaire survey of state DOTs, a delamination percentage of 30 to 50 percent typically defines this point (Hema et al. 2004). Because this level of delamination exceeds the values presented in Figure 4-16 for epoxy-coated bar, estimates for the duration of the second phase of the deterioration process were limited to decks with black bar only. Figure 4-16 indicates that practically all locations with chloride concentrations in the range of 4.0 to 6.0 lb Cl^-/yd^3 of concrete at the level of the top mat of reinforcing steel on a bridge deck with black bar will exhibit delamination; therefore, the lower end of this range may be considered to be the threshold at which delamination occurs. For a given deck, if the average chloride concentration at the level of the top mat of reinforcing steel were to be 4.0 lb Cl^-/yd^3 of concrete, half of the deck would have chloride concentrations greater than 4.0 lb Cl^-/yd^3 of concrete, while half of the deck would have chloride concentrations lower than 4.0 lb Cl^-/yd^3 of concrete. In this case, about 50 percent of the deck area would then be expected to exhibit delamination, and the third phase of the deterioration process would be initiated. Subtracting the duration of the first phase of the deterioration process from the deck age corresponding to the initiation of the third phase of the deterioration process would then yield the duration of the second phase of the deterioration process. The resulting estimated durations of the second phase of the deterioration process are presented in Table 4-2 for each of the same combinations of surface treatment and cover depth presented previously in Table 4-1.

Regarding the performance of epoxy-coated bar, the data in Figure 4-16 clearly demonstrate the benefit of epoxy coatings on reinforcing steel for the purpose of significantly delaying the onset of chloride-induced delamination in concrete bridge decks. Specifically, at chloride concentrations between 4.0 and 6.0 lb Cl^-/yd^3 of concrete, only 4 percent of the test locations involving epoxy-coated bar were delaminated compared to 100 percent of the test

Table 4-2: Duration of Second Phase of Deterioration Process by Surface Treatment Type and Timing and Cover Depth

Surface Treatment Type and Timing	Duration of Second Phase of Deterioration Process (yr)		
	2.0-in. Cover Depth	2.5-in. Cover Depth	3.0-in. Cover Depth
Bare Concrete	4	7	9
Asphalt Overlay Applied Immediately After Construction	27	26	28
Asphalt Overlay Applied 1-10 Years After Construction	25	18	26
Asphalt Overlay Applied 10+ Years After Construction	7	8	9
Polymer Overlay Applied Immediately After Construction	22	27	33
Polymer Overlay Applied 5-10 Years After Construction	12	21	24
Polymer Overlay Applied 10-15 Years After Construction	15.5	19	15
Polymer Overlay Applied 15+ Years After Construction	4.5	6	8

locations involving black bar, and the percentage increases to only 9 percent when epoxy-coated bar is exposed to chloride concentrations exceeding 6.0 lb Cl^-/yd^3 of concrete. These data are generally consistent with the suggestion given in previous research that the chloride concentration threshold for epoxy-coated bar may be four to five times higher than that for black bar (Bentz et al. 2009).

Figure 4-17 presents the relationship between the ratio of chloride concentrations directly above and between steel reinforcing bars and deck age. The data show the relationship between these deck properties as determined at the time of deck testing for 32 test locations on 19 decks where samples were extracted from both directly above the bar and between bars. Eleven decks had polymer overlays, while eight decks had asphalt overlays. All of the decks had epoxy-coated reinforcement, and three of the 32 test locations exhibited delamination. For reference, each data

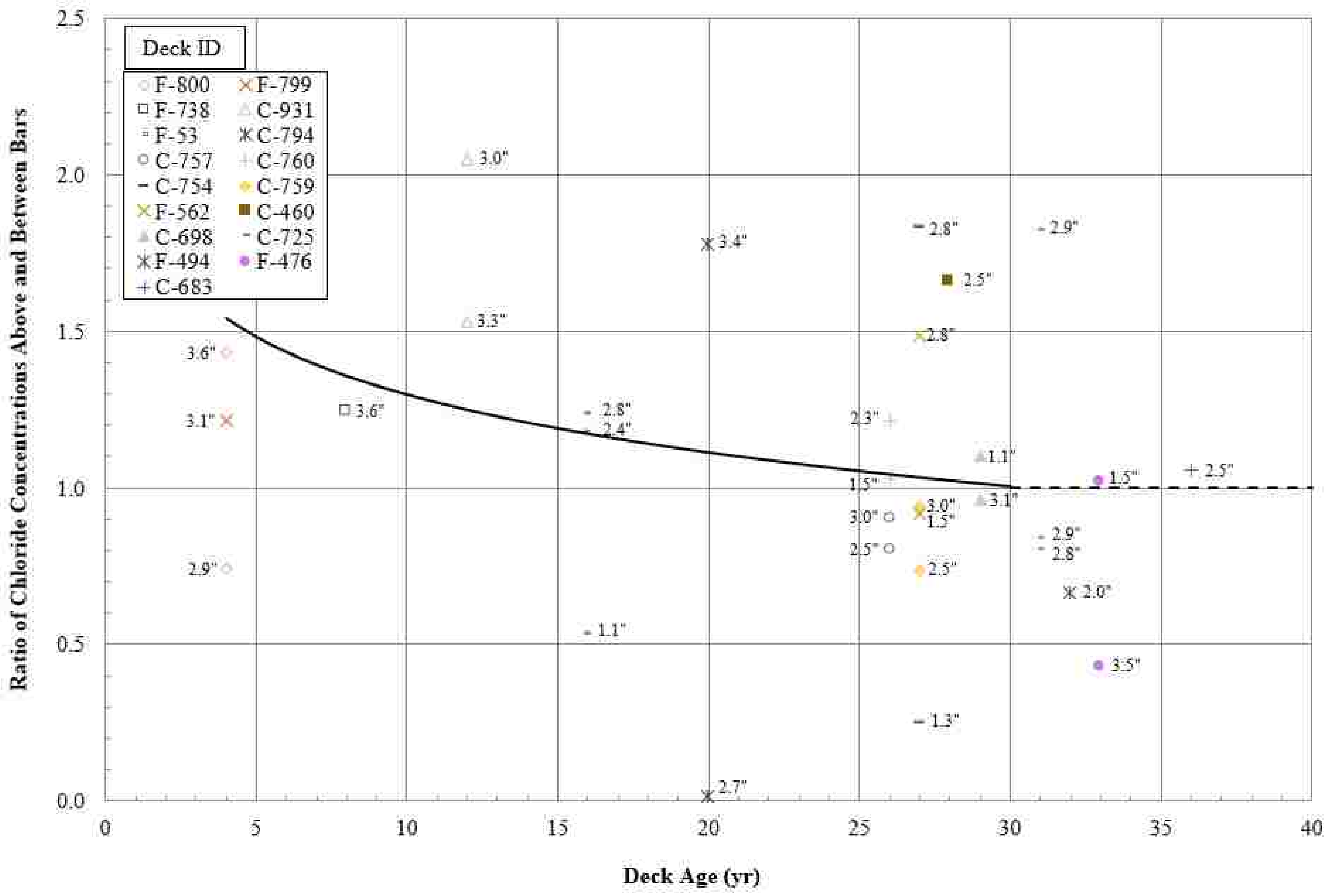

Figure 4-17: Relationship between ratio of chloride concentrations above and between bars and deck age.

point is labeled with the cover depth measured directly above the bar at the testing location. Analysis was independent of surface treatment application timing. Figure 4-17 shows that, as deck age increases, the average ratio of chloride concentrations directly above and between the bars asymptotically decreases from above 1.5 toward 1.0, which is reached at a deck age of approximately 30 years. Given that increasing deck age generally corresponds to increasing chloride concentration, which would in turn eventually lead to similar chloride concentrations directly above and between bars as the concrete pore water within the cover depth approached chloride saturation, this observed relationship is consistent with theory (Ann et al. 2007, Garboczi 1990).

Variability among the individual data points in Figure 4-17 may be attributable to several localized effects. First, the properties of the concrete matrix may not have been homogenous at each test location, which could be a result of variability in the concrete mixture proportions and/or levels of concrete consolidation achieved during construction. Second, during chloride concentration sampling, drilling may not have been performed exactly above the bar as desired; in many cases, the drill bit migrates laterally when hard aggregates are encountered. Third, the occurrence of shallow patching within the cover depth may have affected the results; although none of the test locations on decks for which distress surveys were available were located in patches, distress surveys were not available for multiple decks that were included in this analysis.

Nonetheless, for decks similar to those studied in this research, the data indicate that, on average, chloride concentrations that develop directly above the bars can be even 1.5 times higher than those that develop between the bars in the top mat of reinforcing steel, with the effect being more pronounced at lower deck ages. Understanding the effects of the presence of reinforcing steel on diffusion of chloride ions through the concrete matrix can help inform decisions about chloride concentration thresholds, which, as applied in the analyses previously presented in this research, are often determined from samples obtained between reinforcing bars. Further research is recommended on this subject.

4.4 Summary

The results of this research are based on two to eight chloride concentration samples extracted from each of 526 test locations on 48 bridge decks at which cover depth measurements and sounding were also performed. The concrete bridge decks included in this research were characterized by cover depth and deck age. The majority of the measured cover depths ranged from 1.5 to 3.5 in., with a typical cover depth of approximately 2.5 in. Regarding deck age, the majority of decks tested with polymer and asphalt overlays were older than 20 years of age at the time of testing, while the majority of bare concrete decks were either less than 5 years or greater than 20 years in age.

The data collected from the 48 concrete bridge decks included in this research were used to address both of the objectives stated for this research. Regarding the first objective, baseline relationships between chloride concentration, deck age, and cover depth were developed for bare concrete decks at depths ranging from 0.5 in. to 6.5 in. The results show that, as deck age increases, chloride concentration also increases and that chloride concentrations are much higher for shallower concrete depths, such as 0.5 in. or 1.5 in., than for deeper concrete depths, such as 5.5 in. or 6.5 in., as expected. Based on these relationships, a typical, bare concrete bridge deck in Utah with 2.0-in., 2.5-in., and 3.0-in. cover depth reaches the critical chloride threshold of 2.0 lb Cl^-/yd^3 of concrete at approximately 4, 5, and 7 years, respectively, which would be the duration of the first phase of the deterioration process.

For decks with asphalt or polymer overlays, development of clear relationships between chloride concentration, deck age, and cover depth required consideration of treatment time. Therefore, relationships between chloride concentration and deck age were developed for specific ranges in deck age at the time of treatment. The data show that chloride concentrations for decks that had an asphalt overlay applied 10 or more years after construction are higher than those for decks with an asphalt overlay applied immediately after construction. Regarding the duration of the first phase of the deterioration process, the critical chloride threshold of 2.0 lb Cl^-/yd^3 of concrete for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had an asphalt overlay applied immediately after construction is reached at approximately 33, 38, and 40 years, respectively. Comparatively, the critical chloride threshold for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had an asphalt overlay applied 1 to 10 years after construction is reached at approximately 26, 33, and 40 years, respectively. Chloride concentrations for decks that had a polymer overlay applied 15 or more years after construction are higher than those for decks with a polymer overlay applied immediately after construction. Regarding the duration of the first phase of the deterioration process, the critical chloride threshold of 2.0 lb Cl^-/yd^3 of concrete for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had a polymer overlay applied immediately after construction is reached at approximately 13, 18, and 21 years, respectively. Comparatively, the critical chloride threshold for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had a polymer overlay applied 5 to 10 years after construction is reached at approximately 8, 11, and 15 years, respectively. The critical chloride threshold for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had a polymer overlay applied 10 to 15 years after construction is reached at approximately 5, 7, and 11 years, respectively. Finally, the critical chloride threshold for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had a polymer overlay applied 15 or more years after construction is reached at approximately 4.5, 6, and 8 years, respectively. These results indicate that the deterioration process can be substantially delayed when an overlay is applied immediately or soon after construction.

Relevant to determining the duration of the second phase of the deterioration process, the relationship between delamination occurrence and chloride concentration for bare concrete bridge decks was developed. In general, the results show that the occurrence of delamination increases with increasing chloride concentration. For determining the duration of the second phase of the deterioration process, an extent of deck damage that would initiate the third phase of the deterioration process was defined as 50 percent of the deck area exhibiting delamination. Estimated durations of the second phase of the deterioration process were then determined using a chloride concentration threshold of 4.0 lb Cl^-/yd^3 of concrete for each of the same combinations of surface treatment and cover depth used for determining durations of the first phase of the deterioration process. Regarding the performance of epoxy-coated bar, the data clearly demonstrate the benefit of epoxy coatings on reinforcing steel for the purpose of significantly delaying the onset of chloride-induced delamination in concrete bridge decks.

The relationship between the ratio of chloride concentrations directly above and between steel reinforcing bars and deck age was then developed. The results show that, as deck age increases, the average ratio of chloride concentrations directly above and between the bars asymptotically decreases from above 1.5 toward 1.0, which is reached at a deck age of approximately 30 years. Given that increasing deck age generally corresponds to increasing chloride concentration, which would in turn eventually lead to similar chloride concentrations directly above and between bars as the concrete pore water within the cover depth approached chloride saturation, this observed relationship is consistent with theory.

5 CONCLUSION

5.1 Summary

Chloride-induced deterioration of concrete bridge decks can be described in terms of three phases: 1) initiation of rebar corrosion, 2) rust formation and development of deck damage, and 3) accelerated deck damage towards structural failure. The first objective of this research was to investigate relationships among chloride concentration at the top mat of reinforcing steel, deck age, cover depth, and occurrence of delamination for concrete bridge decks with selected surface treatments and rebar types. Relating these factors can help establish greater understanding about the duration of each phase of the deterioration process. A second objective of this research was to investigate the relationship between chloride concentrations that develop between the bars and those that develop directly above the bars in the top mat of reinforcing steel to better understand the effects of the presence of reinforcing steel on diffusion of chloride ions through the concrete matrix.

This research included extensive data collected from 48 concrete bridge decks in Utah that were tested by the Materials and Pavements Research Group at BYU between the years 2004 and 2017. The deck age ranged from 0 to 47 years at the time of testing. For this research, surface treatment types included bare concrete, thin-bonded polymer overlays, and asphalt overlays, and rebar types included uncoated and epoxy-coated rebar. The bridge decks were analyzed using sounding, cover depth measurements, and chloride concentration testing.

5.2 Findings

The results of this research are based on two to eight chloride concentration samples extracted from each of 526 test locations on 48 bridge decks at which cover depth measurements and sounding were also performed. The concrete bridge decks included in this research were characterized by cover depth and deck age. The majority of the measured cover depths ranged from 1.5 to 3.5 in., with a typical cover depth of approximately 2.5 in. Regarding deck age, the majority of decks tested with polymer and asphalt overlays were older than 20 years of age at the time of testing, while the majority of bare concrete decks were either less than 5 years or greater than 20 years in age.

The data collected from the 48 concrete bridge decks included in this research were used to address both of the objectives stated for this research. Regarding the first objective, baseline relationships between chloride concentration, deck age, and cover depth were developed for bare concrete decks at depths ranging from 0.5 in. to 6.5 in. The results show that, as deck age increases, chloride concentration also increases and that chloride concentrations are much higher for shallower concrete depths, such as 0.5 in. or 1.5 in., than for deeper concrete depths, such as 5.5 in. or 6.5 in., as expected. Based on these relationships, a typical, bare concrete bridge deck in Utah with 2.0-in., 2.5-in., and 3.0-in. cover depth reaches the critical chloride threshold of 2.0 lb Cl^-/yd^3 of concrete at approximately 4, 5, and 7 years, respectively, which would be the duration of the first phase of the deterioration process.

For decks with asphalt or polymer overlays, development of clear relationships between chloride concentration, deck age, and cover depth required consideration of treatment time. Therefore, relationships between chloride concentration and deck age were developed for specific ranges in deck age at the time of treatment. The data show that chloride concentrations for decks that had an asphalt overlay applied 10 or more years after construction are higher than those for decks with an asphalt overlay applied immediately after construction. Regarding the duration of the first phase of the deterioration process, the critical chloride threshold of 2.0 lb Cl^-/yd^3 of concrete for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had an asphalt overlay applied immediately after construction is reached at approximately 33, 38, and 40 years, respectively. Comparatively, the critical chloride threshold for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had an asphalt overlay applied 1 to 10 years after construction is reached at approximately 26, 33, and 40 years, respectively. Chloride concentrations for decks that had a polymer overlay applied 15 or more years after construction are higher than those for decks with a polymer overlay applied immediately after construction. Regarding the duration of the first phase of the deterioration process, the critical chloride threshold of 2.0 lb Cl^-/yd^3 of concrete for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had a polymer overlay applied immediately after construction is reached at approximately 13, 18, and 21 years, respectively. Comparatively, the critical chloride threshold for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had a polymer overlay applied 5 to 10 years after construction is reached at approximately 8, 11, and 15 years, respectively. The critical chloride threshold for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had a polymer overlay applied 10 to 15 years after construction is reached at approximately 5, 7, and 11 years, respectively. Finally, the critical chloride threshold for decks with 2.0-in., 2.5-in., and 3.0-in. cover depth that had a polymer overlay applied 15 or more years after construction is reached at approximately 4.5, 6, and 8 years, respectively. These results indicate that the deterioration process can be substantially delayed when an overlay is applied immediately or soon after construction.

Relevant to determining the duration of the second phase of the deterioration process, the relationship between delamination occurrence and chloride concentration for bare concrete bridge decks was developed. In general, the results show that the occurrence of delamination increases with increasing chloride concentration. For determining the duration of the second phase of the deterioration process, an extent of deck damage that would initiate the third phase of the deterioration process was defined as 50 percent of the deck area exhibiting delamination. Estimated durations of the second phase of the deterioration process were then determined using a chloride concentration threshold of 4.0 lb Cl^-/yd^3 of concrete for each of the same combinations of surface treatment and cover depth used for determining durations of the first phase of the deterioration process. Regarding the performance of epoxy-coated bar, the data clearly demonstrate the benefit of epoxy coatings on reinforcing steel for the purpose of significantly delaying the onset of chloride-induced delamination in concrete bridge decks.

The relationship between the ratio of chloride concentrations directly above and between steel reinforcing bars and deck age was then developed. The results show that, as deck age increases, the average ratio of chloride concentrations directly above and between the bars asymptotically decreases from above 1.5 toward 1.0, which is reached at a deck age of approximately 30 years. Given that increasing deck age generally corresponds to increasing chloride concentration, which would in turn eventually lead to similar chloride concentrations directly above and between bars as the concrete pore water within the cover depth approached chloride saturation, this observed relationship is consistent with theory.

5.3 Recommendations

Given the findings of this research, UDOT may be able to enhance programming of concrete bridge deck preservation actions based on deck age, cover depth, surface treatment type and timing, and rebar type, given that an increasing number of bridges will require rehabilitation or reconstruction in the coming years. UDOT should continue to utilize surface treatments and epoxy-coated rebar to delay deterioration of bare concrete bridge decks; the benefits of early applications of surface treatments are especially apparent in the results of this research. Further research about the implications of chloride concentration sampling location, directly above bar or between bars, for concrete bridge deck management is also recommended.

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APPENDIX BRIDGE DECK DATA

Table A-1: Detailed Bridge Deck Data

Deck ID	Test Location	Above Bar (Yes/No)	Cover Depth (in.)	Delamination (Yes/No)	Chloride Concentration (lb Cl^{-}/yd^{3} of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
F-330	(40, 6)	No	4.3	No	4.662	2.398	1.389	0.765	0.737	0.417	0.292
F-330	(100, 22)	Yes	3.1	No	5.500	3.382	1.786	0.705	0.559	-	-
F-330	(300, 6)	No	3.5	No	4.536	0.235	0.178	0.174	0.211	0.640	0.259
F-330	(355, 16)	No	3.4	Yes	0.814	0.215	0.571	8.975	9.048	7.047	9.056
F-330	(500, 12)	No	3.6	No	4.423	0.255	0.198	0.198	0.154	0.231	0.324
F-330	(503, 2)	No	3.4	Yes	11.109	2.155	0.474	0.583	0.316	0.300	0.211
F-330	(608, 6)	No	2.9	Yes	1.494	2.880	3.430	2.657	3.321	3.479	3.600
F-330	(660, 12)	No	3.3	No	0.794	0.243	0.304	0.312	1.656	3.248	4.103
F-330	(678, 20)	No	3.6	Yes	0.660	0.279	0.235	3.001	3.309	2.819	2.491
F-330	(920, 8)	No	3.4	No	5.512	0.486	0.073	0.421	0.324	0.186	0.190
F-330	(1215, 12)	No	3.4	Yes	6.768	9.068	3.957	3.600	2.940	2.377	2.475
F-330	(1372, 14)	No	2.9	Yes	12.450	5.540	2.645	1.786	1.551	1.150	1.017
F-799 (SB)	1	No	2.3	-	4.149	-	-	-	-	-	-
F-799 (SB)	2	No	2.5	-	3.661	-	-	-	-	-	-
F-799 (SB)	3	No	2.4	-	5.745	-	-	-	-	-	-
F-799 (SB)	4	No	2.4	-	7.829	-	-	-	-	-	-
F-799 (NB)	1	No	2.7	-	3.633	-	-	-	-	-	-
F-799 (NB)	2	No	2.7	-	3.515	-	-	-	-	-	-
F-799 (NB)	3	No	2.5	-	5.850	-	-	-	-	-	-
F-799 (NB)	4	No	2.6	-	5.727	-	-	-	-	-	-

Deck ID	Test Loca-tion	Above Bar (Yes/ No)	Cover Depth (in.)	Delam-ination (Yes/ No)	Chloride Concentration (lb Cl-/yd³ of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
F-800 (SB)	1	No	3.5	-	3.418	-	-	-	-	-	-

Table A-2: Detailed Bridge Deck Data (Continued)

Deck ID	Test Loca-tion	Above Bar (Yes/ No)	Cover Depth (in.)	Delam-ination (Yes/ No)	Chloride Concentration (lb Cl-/yd³ of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
F-800 (SB)	2	No	3.4	-	5.225	-	-	-	-	-	-
F-800 (SB)	3	No	3.4	-	7.772	-	-	-	-	-	-
F-800 (SB)	4	No	3.4	-	5.982	-	-	-	-	-	-
F-800 (NB)	1	No	2.8	-	4.931	-	-	-	-	-	-
F-800 (NB)	2	No	2.8	-	5.417	-	-	-	-	-	-
F-800 (NB)	3	No	2.7	-	5.344	-	-	-	-	-	-
F-800 (NB)	4	No	2.7	-	6.812	-	-	-	-	-	-
F-799 (SB)	1	No	2.4	-	7.300	-	-	-	-	-	-
F-799 (SB)	2	No	2.4	-	10.801	-	-	-	-	-	-
F-799 (SB)	3	No	2.4	-	8.053	-	-	-	-	-	-
F-799 (SB)	4	No	2.4	-	7.752	-	-	-	-	-	-
F-799 (NB)	1	No	2.6	-	5.719	-	-	-	-	-	-
F-799 (NB)	2	No	2.6	-	9.234	-	-	-	-	-	-
F-799 (NB)	3	No	2.6	-	6.715	-	-	-	-	-	-
F-799 (NB)	4	No	2.6	-	8.995	-	-	-	-	-	-
F-800 (SB)	1	No	3.4	-	6.350	-	-	-	-	-	-
F-800 (SB)	2	No	3.4	-	9.680	-	-	-	-	-	-
F-800 (SB)	3	No	3.4	-	6.290	-	-	-	-	-	-
F-800 (SB)	4	No	3.4	-	5.322	-	-	-	-	-	-
F-800 (NB)	1	No	2.7	-	8.414	-	-	-	-	-	-
F-800 (NB)	2	No	2.7	-	7.387	-	-	-	-	-	-
F-800 (NB)	3	No	2.7	-	7.900	-	-	-	-	-	-
F-800 (NB)	4	No	2.7	-	11.006	-	-	-	-	-	-
F-799 (SB)	1	No	2.4	-	8.104	-	-	-	-	-	-

F-799 (SB)	2	No	2.4	-	6.940	-	-	-	-	-	-

Table A-3: Detailed Bridge Deck Data (Continued)

Deck ID	Test Loca-tion	Above Bar (Yes/ No)	Cover Depth (in.)	Delam-ination (Yes/ No)	Chloride Concentration (lb Cl-/yd3 of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
F-799 (SB)	3	No	2.4	-	11.269	-	-	-	-	-	-
F-799 (SB)	4	No	2.4	-	10.862	-	-	-	-	-	-
F-799 (NB)	1	No	2.6	-	6.399	-	-	-	-	-	-
F-799 (NB)	2	No	2.6	-	5.761	-	-	-	-	-	-
F-799 (NB)	3	No	2.6	-	5.285	-	-	-	-	-	-
F-799 (NB)	4	No	2.6	-	10.560	-	-	-	-	-	-
F-800 (SB)	1	No	3.4	-	4.342	-	-	-	-	-	-
F-800 (SB)	2	No	3.4	-	5.036	-	-	-	-	-	-
F-800 (SB)	3	No	3.4	-	10.477	-	-	-	-	-	-
F-800 (SB)	4	No	3.4	-	8.300	-	-	-	-	-	-
F-800 (NB)	1	No	2.7	-	7.146	-	-	-	-	-	-
F-800 (NB)	2	No	2.7	-	8.916	-	-	-	-	-	-
F-800 (NB)	3	No	2.7	-	10.773	-	-	-	-	-	-
F-800 (NB)	4	No	2.7	-	7.373	-	-	-	-	-	-
C-438	17	No	1.7	No	13.037	1.718	0.336	0.184	-	-	-
C-438	34	No	2.1	No	10.690	2.141	0.186	0.154	-	-	-
C-438	66	No	2.2	No	20.089	3.967	0.322	0.210	-	-	-
C-438	83	No	3.1	No	15.491	4.116	0.389	0.176	-	-	-
C-438	96	No	2.2	No	14.954	2.817	0.189	0.153	-	-	-
C-438	109	No	2.7	No	16.336	6.220	0.863	0.122	-	-	-
C-844	47	No	2.6	No	13.517	1.079	0.331	0.250	-	-	-
C-844	92	No	2.7	No	20.427	1.222	0.219	0.213	-	-	-
C-844	180	No	2.4	No	15.321	5.348	2.748	1.421	-	-	-
C-844	226	No	2.6	No	12.789	2.055	0.377	-	-	-	-
C-844	264	No	2.6	No	13.205	1.356	0.333	0.441	-	-	-
C-844	299	No	2.4	No	20.567	1.720	0.384	0.452	-	-	-
C-919	4	No	1.9	No	13.665	1.597	0.669	0.124	-	-	-
C-919	9	No	2.9	No	14.529	1.330	0.201	0.213	-	-	-
C-919	17	No	2.6	No	12.142	0.166	0.258	0.210	-	-	-
C-919	22	No	3.2	No	15.174	0.712	0.104	0.111	-	-	-

C-919	25	No	2.9	No	11.824	0.682	0.180	0.235	-	-	-
C-919	30A	No	3.8	No	12.742	1.335	0.194	0.133	-	-	-

Table A-4: Detailed Bridge Deck Data (Continued)

Deck ID	Test Loca-tion	Above Bar (Yes/ No)	Cover Depth (in.)	Delam-ination (Yes/ No)	Chloride Concentration (lb Cl^{-}/yd^{3} of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
C-726	19	No	1.7	No	19.782	16.491	8.906	2.063	0.074	0.033	0.045
C-726	38	No	1.8	No	18.679	13.203	7.164	2.414	0.588	0.081	0.043
C-726	75	No	2.0	No	24.966	19.939	12.519	5.388	1.070	0.082	0.042
C-726	94	No	2.4	No	20.586	14.513	4.317	0.780	0.468	0.051	0.052
C-726	110	No	2.2	No	22.895	13.845	4.261	0.687	0.044	0.032	0.036
C-726	124	No	2.0	No	16.729	9.492	5.300	1.721	0.194	0.043	0.041
F-500	7A	No	2.7	No	6.852	0.192	0.065	0.050	0.057	0.041	0.034
F-500	14	No	2.4	No	8.376	2.205	0.472	0.093	0.048	0.046	0.054
F-500	27	No	2.5	No	13.788	0.244	0.037	0.044	0.027	0.033	0.045
F-500	34	No	2.4	No	9.168	0.586	0.058	0.057	0.053	0.062	0.084
F-500	40	No	2.3	No	9.932	2.101	0.258	0.075	0.057	0.046	0.051
F-500	45	No	2.4	No	11.392	0.271	0.036	0.090	0.081	0.064	0.080
F-504	12A	No	2.1	No	17.713	6.521	1.273	0.047	0.037	0.031	0.029
F-504	23	No	2.4	No	21.144	13.073	5.050	1.376	0.151	0.040	0.041
F-504	46A	No	2.7	No	23.268	10.719	2.991	0.672	0.114	0.051	0.043
F-504	57	No	2.9	No	14.358	5.829	2.732	0.678	0.131	0.069	0.070
F-504	67	No	2.7	No	21.730	15.932	7.610	3.059	0.534	0.038	0.047
F-504	76	No	2.3	No	16.148	7.397	3.096	0.967	0.124	0.059	0.043
F-506	12	No	2.3	No	9.555	1.941	0.142	0.049	0.049	0.026	0.032
F-506	24A	No	2.9	No	18.659	11.209	2.661	0.289	0.083	-	-
F-506	46A	No	2.7	No	24.000	10.553	1.495	0.171	0.066	0.049	0.058
F-506	58	No	2.3	No	17.091	6.562	1.145	1.286	0.038	0.036	0.042
F-506	68A	No	3.1	No	22.663	13.034	0.049	0.056	0.076	0.065	0.079
F-506	77	No	3.0	No	15.055	7.991	3.255	1.011	0.066	0.049	0.030
C-460	11	No	2.2	No	13.883	4.462	0.828	0.061	0.035	0.042	0.050
C-460	22	No	1.7	No	21.516	12.368	5.209	2.104	0.669	0.030	0.029
C-460	43	No	1.3	No	21.947	11.290	5.828	1.744	0.434	0.251	0.070
C-460	54A	No	1.7	No	24.892	16.340	7.896	5.046	3.196	1.988	1.687
C-460	64	No	1.4	No	17.084	5.225	1.228	0.409	0.079	0.053	0.052
C-460	72	No	1.9	No	26.167	10.133	3.121	0.622	0.087	0.060	0.060
C-688	11	No	2.6	No	15.472	5.451	2.520	0.243	0.076	0.076	0.072
C-688	21	No	2.4	No	26.958	17.889	8.216	2.301	0.395	0.199	0.062
C-688	41	No	2.6	No	15.525	9.385	5.068	2.895	1.384	0.531	0.285
C-688	52A	No	3.2	No	19.650	8.866	3.776	1.143	0.216	0.065	0.056
C-688	60	No	3.3	No	14.931	7.921	5.937	4.043	2.436	0.935	0.445
C-688	79	No	3.3	No	18.287	9.597	4.168	0.930	0.154	0.038	0.031
C-698	7	No	1.9	No	30.824	19.867	8.352	3.078	0.909	0.135	0.038

C-698	15	No	2.1	No	27.941	15.510	6.942	2.380	0.481	0.079	0.059
C-698	29A	No	1.9	No	31.146	23.022	13.111	6.960	3.059	0.966	0.273
C-698	36	No	1.9	No	27.352	15.674	7.253	2.941	0.605	0.157	0.045
C-698	42	No	2.0	No	17.643	9.015	4.468	1.505	0.333	0.072	0.070

Table A-5: Detailed Bridge Deck Data (Continued)

Deck ID	Test Loca-tion	Above Bar (Yes/ No)	Cover Depth (in.)	Delam-ination (Yes/ No)	Chloride Concentration (lb Cl^-/yd^3 of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
C-698	48A	No	2.4	No	24.224	10.044	5.894	3.188	0.964	0.351	0.058
C-699	12	No	1.7	No	14.638	4.236	3.042	0.583	0.186	0.099	0.086
C-699	22	No	1.7	No	26.546	21.654	13.219	5.570	2.295	0.339	-
C-699	44	No	2.5	No	22.442	14.639	6.909	3.177	0.774	0.119	0.030
C-699	54	No	2.0	No	26.447	20.682	11.764	5.080	1.472	0.297	0.064
C-699	64	No	2.8	No	18.310	10.058	5.064	2.761	0.524	0.137	0.079
C-699	72	No	2.8	No	29.474	19.539	14.209	9.626	4.666	2.515	1.622
C-760	9A	No	2.0	No	35.396	21.182	12.739	5.873	2.286	0.623	0.249
C-760	17	No	1.8	No	26.681	14.017	6.338	2.058	0.228	0.049	0.050
C-760	33	No	1.8	No	30.728	18.193	9.876	5.223	1.836	0.660	0.277
C-760	42	No	1.5	No	31.820	18.279	9.746	4.427	1.402	0.342	0.131
C-760	49	No	2.1	No	20.357	14.398	7.733	3.960	1.962	0.858	0.369
C-760	56	No	1.8	No	16.010	8.074	3.640	1.459	0.349	0.095	0.080
F-205	I36	No	2.2	No	0.791	0.277	0.161	0.087	-	-	-
F-205	D34	No	2.3	No	0.329	0.161	0.142	0.130	0.269	0.168	0.262
F-205	E24	No	1.5	No	0.388	0.194	0.316	0.129	-	-	-
F-205	R20	No	1.6	No	0.612	0.200	0.166	0.109	-	-	-
F-205	T80	No	1.4	No	0.835	0.382	0.267	0.148	-	-	-
F-205	O56	No	1.6	No	1.284	0.836	0.198	0.164	-	-	-
F-205	D8	No	1.5	No	0.335	0.221	0.233	0.211	-	-	-
F-205	P44	No	1.5	No	0.477	0.161	0.182	0.226	-	-	-
F-205	R32	No	1.7	No	1.701	0.615	0.278	0.211	-	-	-
C-357	A1	No	1.7	No	2.351	1.411	1.045	0.484	-	-	-
C-357	B1	No	1.7	No	2.371	1.533	0.851	0.735	-	-	-
C-357	C1	No	1.7	No	1.867	1.663	0.861	1.122	-	-	-
C-357	D1	No	1.8	No	2.144	1.897	1.221	0.834	-	-	-
C-357	E1	No	1.7	No	2.096	2.764	2.219	1.243	-	-	-
C-357	A2	No	1.7	No	2.153	1.351	1.140	0.729	-	-	-
C-357	B2	No	1.7	No	2.230	1.867	1.383	0.927	-	-	-
C-357	C2	No	1.6	No	1.841	2.614	1.191	1.100	-	-	-
C-357	D2	No	1.6	No	2.438	1.739	1.312	0.958	-	-	-
C-357	E2	No	1.4	No	2.590	3.084	2.082	1.623	-	-	-
C-357	A3	No	1.6	No	2.051	0.944	0.859	0.563	-	-	-
C-357	B3	No	1.5	No	1.991	1.652	0.834	0.739	-	-	-
C-357	C3	No	1.4	No	1.772	2.313	1.466	1.229	-	-	-
C-357	D3	No	1.3	No	2.527	2.677	1.316	1.278	-	-	-
C-357	E3	No	1.4	No	2.738	3.200	1.758	1.415	-	-	-
C-357	A4	No	1.8	No	1.825	1.300	0.826	0.281	-	-	-

C-357	B4	No	1.6	No	1.849	1.671	0.986	0.672	-	-	-
C-357	C4	No	1.5	No	2.118	2.256	1.302	1.041	-	-	-
C-357	D4	No	1.5	No	2.153	1.922	1.557	1.379	-	-	-
C-357	E4	No	1.4	No	2.624	2.819	1.705	1.369	-	-	-

Table A-6: Detailed Bridge Deck Data (Continued)

Deck ID	Test Loca-tion	Above Bar (Yes/ No)	Cover Depth (in.)	Delam-ination (Yes/ No)	Chloride Concentration (lb Cl^-/yd^3 of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
C-357	A5	No	1.7	No	1.575	1.132	0.887	0.435	-	-	-
C-357	B5	No	1.6	No	2.347	1.330	1.081	0.648	-	-	-
C-357	C5	No	1.5	No	2.379	2.661	2.142	1.268	-	-	-
C-357	D5	No	1.5	No	2.511	2.673	1.654	1.079	-	-	-
C-357	E5	No	1.4	No	2.130	3.149	2.458	1.675	-	-	-
C-357	A6	No	1.7	No	1.970	1.389	0.832	0.443	-	-	-
C-357	B6	No	1.6	No	1.987	1.379	0.887	0.622	-	-	-
C-357	C6	No	1.5	No	2.578	2.438	1.369	1.019	-	-	-
C-357	D6	No	1.4	No	2.452	2.594	1.351	1.021	-	-	-
C-357	E6	No	1.4	No	3.133	3.380	2.084	1.233	-	-	-
C-357	A7	No	1.7	No	2.499	2.025	1.142	0.676	-	-	-
C-357	B7	No	1.6	No	1.946	2.452	1.213	0.816	-	-	-
C-357	C7	No	1.5	No	2.185	2.264	1.328	0.978	-	-	-
C-357	D7	No	1.4	No	1.654	1.191	1.118	0.713	-	-	-
C-357	E7	No	1.3	No	0.662	1.590	1.912	1.474	-	-	-
C-357	A8	No	1.6	No	2.422	2.313	1.256	0.875	-	-	-
C-357	B8	No	1.6	No	2.519	2.193	1.523	1.019	-	-	-
C-357	C8	No	1.4	No	2.234	2.730	1.865	1.053	-	-	-
C-357	B9	No	1.5	No	2.189	2.604	1.304	0.800	-	-	-
C-357	D8	No	1.4	No	0.942	1.677	1.312	0.899	-	-	-
C-357	E8	No	1.3	Yes	0.498	0.832	1.980	1.474	-	-	-
C-357	A9	No	1.6	No	2.138	2.309	1.258	0.887	-	-	-
C-357	C9	No	1.4	Yes	2.626	2.833	1.383	1.067	-	-	-
C-357	D9	No	1.4	Yes	2.873	2.768	1.737	1.302	-	-	-
C-357	E9	No	1.3	Yes	3.038	2.734	2.104	1.608	-	-	-
C-363	A1	No	1.1	No	0.956	0.393	0.381	0.239	-	-	-
C-363	B1	No	1.4	No	0.634	0.373	-	-	-	-	-
C-363	C1	No	1.4	No	0.830	0.482	-	-	-	-	-
C-363	D1	No	1.2	No	0.942	0.508	-	-	-	-	-
C-363	E1	No	1.1	No	0.970	0.539	-	-	-	-	-
C-363	A2	No	1.1	No	0.905	0.093	0.247	0.172	-	-	-
C-363	B2	No	1.2	No	0.583	0.468	-	-	-	-	-
C-363	C2	No	1.4	No	0.857	0.286	-	-	-	-	-
C-363	D2	No	1.2	No	0.851	0.522	-	-	-	-	-
C-363	E2	No	1.1	No	0.978	0.644	-	-	-	-	-
C-363	A3	No	1.2	No	1.015	0.458	0.356	0.527	-	-	-
C-363	B3	No	1.4	No	0.484	0.286	-	-	-	-	-
C-363	C3	No	1.6	No	0.474	0.296	-	-	-	-	-

C-363	D3	No	1.3	No	1.061	0.360	-	-	-	-	-
C-363	E3	No	1.1	No	0.709	0.334	-	-	-	-	-
C-363	A4	No	1.4	No	1.156	0.350	0.340	0.290	-	-	-
C-363	B4	No	1.6	No	0.579	0.634	-	-	-	-	-

Table A-7: Detailed Bridge Deck Data (Continued)

Deck ID	Test Loca-tion	Above Bar (Yes/ No)	Cover Depth (in.)	Delam-ination (Yes/ No)	Chloride Concentration (lb Cl^-/yd^3 of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
C-363	C3	No	1.6	No	0.474	0.296	-	-	-	-	-
C-363	D3	No	1.3	No	1.061	0.360	-	-	-	-	-
C-363	E3	No	1.1	No	0.709	0.334	-	-	-	-	-
C-363	A4	No	1.4	No	1.156	0.350	0.340	0.290	-	-	-
C-363	B4	No	1.6	No	0.579	0.634	-	-	-	-	-
C-363	C4	No	1.7	No	0.678	0.393	-	-	-	-	-
C-363	D4	No	1.4	No	0.871	0.277	-	-	-	-	-
C-363	E4	No	1.1	No	2.149	0.531	-	-	-	-	-
C-363	A5	No	1.7	No	0.895	0.275	0.371	0.292	-	-	-
C-363	B5	No	1.7	No	0.686	0.391	-	-	-	-	-
C-363	C5	No	1.7	No	0.733	0.334	-	-	-	-	-
C-363	D5	No	1.3	No	0.462	0.186	-	-	-	-	-
C-363	E5	No	1.2	No	0.691	0.356	-	-	-	-	-
C-363	A6	No	1.5	No	2.189	0.401	0.375	0.705	-	-	-
C-363	B6	No	1.5	No	0.778	0.367	-	-	-	-	-
C-363	C6	No	1.4	No	0.616	0.130	-	-	-	-	-
C-363	D6	No	1.2	No	0.711	0.356	-	-	-	-	-
C-363	E6	No	1.1	No	0.889	0.342	-	-	-	-	-
C-363	A7	No	1.5	No	1.549	0.510	0.354	0.281	-	-	-
C-363	B7	No	1.5	No	0.725	0.314	-	-	-	-	-
C-363	C7	No	1.2	No	0.634	0.281	-	-	-	-	-
C-363	D7	No	1.2	No	0.294	0.241	-	-	-	-	-
C-363	E7	No	1.2	No	1.002	0.286	-	-	-	-	-
C-363	A8	No	1.2	No	0.776	0.350	0.326	0.318	-	-	-
C-363	B8	No	1.4	No	0.654	0.166	-	-	-	-	-
C-363	C8	No	1.3	No	0.869	0.486	-	-	-	-	-
C-363	D8	No	1.2	No	0.840	0.616	-	-	-	-	-
C-363	E8	No	1.2	No	0.721	0.417	-	-	-	-	-
C-363	A9	No	1.1	No	0.794	0.387	0.448	0.288	-	-	-
C-363	B9	No	1.3	No	0.555	0.350	-	-	-	-	-
C-363	C9	No	1.4	No	1.067	0.482	-	-	-	-	-
C-363	D9	No	1.2	No	0.934	0.573	-	-	-	-	-
C-363	E9	No	1.3	No	0.798	0.385	-	-	-	-	-
C-358	A1	No	2.2	Yes	7.412	8.199	5.599	5.668	-	-	-
C-358	B1	No	2.3	Yes	6.725	5.998	5.439	5.214	-	-	-
C-358	C1	No	2.3	Yes	4.824	6.223	5.694	5.796	-	-	-
C-358	D1	No	2.3	Yes	3.716	4.688	3.973	4.493	-	-	-
C-358	E1	No	2.3	Yes	3.449	3.602	3.870	4.176	-	-	-

C-358	A2	No	1.9	Yes	9.767	7.796	6.431	4.218	-	-	-
C-358	B2	No	1.9	Yes	7.648	7.632	5.229	4.382	-	-	-
C-358	C2	No	1.9	Yes	5.352	6.124	5.775	4.878	-	-	-
C-358	D2	No	1.9	Yes	4.190	3.744	2.744	2.450	-	-	-

Table A-8: Detailed Bridge Deck Data (Continued)

Deck ID	Test Loca-tion	Above Bar (Yes/ No)	Cover Depth (in.)	Delam-ination (Yes/ No)	Chloride Concentration (lb Cl^-/yd^3 of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
C-358	E2	No	2.0	Yes	3.519	4.127	3.789	2.714	-	-	-
C-358	A3	No	1.9	Yes	6.907	7.252	5.980	5.058	-	-	-
C-358	B3	No	1.8	Yes	6.646	5.986	5.095	4.947	-	-	-
C-358	C3	No	2.0	Yes	4.898	5.405	4.994	4.329	-	-	-
C-358	D3	No	2.2	Yes	4.880	5.129	3.540	3.021	-	-	-
C-358	E3	No	2.2	Yes	4.704	4.880	3.746	3.410	-	-	-
C-358	A4	No	2.1	Yes	7.282	6.845	5.216	7.029	-	-	-
C-358	B4	No	2.0	Yes	5.753	6.020	5.117	5.225	-	-	-
C-358	C4	No	2.2	Yes	5.589	5.310	4.093	4.759	-	-	-
C-358	D4	No	2.2	Yes	4.662	5.615	4.192	3.677	-	-	-
C-358	E4	No	2.1	Yes	4.826	4.360	4.556	3.900	-	-	-
C-358	A5	No	2.4	Yes	6.575	7.821	4.477	4.660	-	-	-
C-358	B5	No	2.1	Yes	4.868	5.352	5.808	4.645	-	-	-
C-358	C5	No	2.3	Yes	4.125	4.536	4.809	4.562	-	-	-
C-358	D5	No	2.3	Yes	4.066	4.558	4.933	5.077	-	-	-
C-358	E5	No	2.2	Yes	3.967	4.392	4.202	4.520	-	-	-
C-358	A6	No	2.3	Yes	3.438	6.984	5.779	3.706	-	-	-
C-358	B6	No	2.3	Yes	4.180	5.046	5.518	7.047	-	-	-
C-358	C6	No	2.5	Yes	3.609	4.643	4.609	3.839	-	-	-
C-358	D6	No	2.4	Yes	2.825	4.518	4.376	4.255	-	-	-
C-358	E6	No	2.5	Yes	4.048	4.587	3.916	5.461	-	-	-
C-358	A7	No	2.4	Yes	4.583	5.852	4.860	5.551	-	-	-
C-358	B7	No	2.5	Yes	4.311	4.870	4.396	3.708	-	-	-
C-358	C7	No	2.5	Yes	2.930	3.546	4.275	3.068	-	-	-
C-358	D7	No	2.7	Yes	2.359	3.331	3.868	3.104	-	-	-
C-358	E7	No	2.8	Yes	3.552	4.459	4.163	3.657	-	-	-
C-358	A8	No	2.4	Yes	5.004	6.201	5.670	5.638	-	-	-
C-358	B8	No	2.7	Yes	3.702	4.734	4.696	5.575	-	-	-
C-358	C8	No	2.5	Yes	3.133	4.086	4.498	5.065	-	-	-
C-358	D8	No	2.5	Yes	3.148	4.172	4.125	4.805	-	-	-
C-358	E8	No	2.6	Yes	2.916	4.212	3.659	4.884	-	-	-
C-358	A9	No	2.6	Yes	4.996	5.986	5.658	5.530	-	-	-
C-358	B9	No	2.5	Yes	5.050	6.030	5.700	6.203	-	-	-
C-358	C9	No	2.8	Yes	3.331	4.512	3.904	4.591	-	-	-
C-358	D9	No	2.5	Yes	4.137	4.858	3.588	5.121	-	-	-
C-358	E9	No	2.6	Yes	2.742	3.637	4.060	3.760	-	-	-
D-413	A1	No	2.1	No	8.904	8.005	6.926	5.192	-	-	-
D-413	B1	No	2.1	Yes	5.972	7.112	5.777	2.971	-	-	-

D-413	C1	No	2.2	No	5.407	1.345	0.247	0.186	-	-	-
D-413	D1	No	2.3	No	4.637	1.021	0.142	0.144	-	-	-
D-413	E1	No	2.2	No	7.596	6.800	3.876	0.682	-	-	-

Table A-9: Detailed Bridge Deck Data (Continued)

Deck ID	Test Loca-tion	Above Bar (Yes/ No)	Cover Depth (in.)	Delam-ination (Yes/ No)	Chloride Concentration (lb Cl^-/yd^3 of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
D-413	A2	No	2.2	No	6.359	4.854	1.960	0.632	-	-	-
D-413	B2	No	2.2	No	7.574	5.024	2.442	0.547	-	-	-
D-413	C2	No	2.3	No	2.849	0.247	0.251	0.221	-	-	-
D-413	D2	No	2.2	No	3.238	0.593	0.213	0.229	-	-	-
D-413	E2	No	2.2	No	7.993	5.263	4.664	2.414	-	-	-
D-413	A3	No	2.2	No	7.983	5.949	5.135	3.135	-	-	-
D-413	B3	No	2.0	No	5.474	6.221	4.078	0.745	-	-	-
D-413	C3	No	2.2	No	2.841	0.672	0.312	0.223	-	-	-
D-413	D3	No	2.2	No	3.639	2.353	1.033	0.411	-	-	-
D-413	E3	No	2.2	No	7.954	4.396	5.877	4.366	-	-	-
D-413	A4	No	2.0	No	7.440	5.575	4.489	2.112	-	-	-
D-413	B4	No	2.1	No	6.354	6.531	4.698	2.685	-	-	-
D-413	C4	No	2.1	No	6.437	3.325	2.833	0.628	-	-	-
D-413	D4	No	2.2	No	4.161	3.366	0.654	0.717	-	-	-
D-413	E4	No	2.3	No	6.699	8.398	8.839	6.826	-	-	-
D-413	A5	No	2.1	No	6.510	6.192	5.686	2.669	-	-	-
D-413	B5	No	2.1	No	5.445	6.030	5.528	3.803	-	-	-
D-413	C5	No	1.1	No	4.769	4.153	2.173	0.824	-	-	-
D-413	D5	No	2.2	No	4.228	9.380	7.620	4.990	-	-	-
D-413	E5	No	2.1	No	6.103	9.250	7.436	5.877	-	-	-
D-413	A6	No	1.9	No	6.909	6.871	6.225	4.228	-	-	-
D-413	B6	No	2.2	No	7.539	16.615	19.740	11.212	-	-	-
D-413	C6	No	2.2	No	4.795	3.856	2.843	1.156	-	-	-
D-413	D6	No	2.0	No	4.649	4.846	3.402	1.310	-	-	-
D-413	E6	No	1.9	No	6.575	10.018	10.674	8.716	-	-	-
D-413	A7	No	1.9	No	7.567	6.903	6.306	4.062	-	-	-
D-413	B7	No	1.9	No	6.676	8.323	6.425	5.674	-	-	-
D-413	C7	No	2.1	No	3.918	3.123	2.021	0.701	-	-	-
D-413	D7	No	2.2	No	4.749	4.591	2.268	0.885	-	-	-
D-413	E7	No	1.9	No	6.057	6.286	4.913	4.992	-	-	-
D-413	A8	No	1.4	No	6.409	7.612	8.475	5.919	-	-	-
D-413	B8	No	2.1	No	5.425	7.286	6.012	9.923	-	-	-
D-413	C8	No	2.2	No	2.746	1.185	0.755	0.263	-	-	-
D-413	D8	No	2.0	No	4.188	4.585	2.912	1.104	-	-	-
D-413	E8	No	1.9	No	5.370	7.162	5.146	2.078	-	-	-
D-413	A9	No	1.9	No	9.115	7.630	7.019	5.897	-	-	-
D-413	B9	No	1.9	No	9.680	6.379	6.243	4.811	-	-	-
D-413	C9	No	1.9	No	3.910	4.042	2.078	1.661	-	-	-
D-413	D9	No	2.0	No	2.938	5.551	4.064	3.424	-	-	-

D-413	E9	No	2.0	No	7.859	7.450	8.339	10.394	-	-	-
F-402	1L	No	2.4	No	27.613	27.038	13.276	5.796	1.863	0.279	-

Table A-10: Detailed Bridge Deck Data (Continued)

Deck ID	Test Loca-tion	Above Bar (Yes/ No)	Cover Depth (in.)	Delam-ination (Yes/ No)	Chloride Concentration (lb Cl-/yd³ of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
F-402	1R	No	2.8	No	11.838	18.978	15.285	7.529	0.863	0.138	-
F-402	2L	No	2.8	No	17.038	22.623	13.057	7.553	2.398	0.012	-
F-402	2R	No	3.0	No	33.133	20.173	6.776	0.960	0.348	0.385	-
C-683	1L	No	2.9	No	8.951	2.195	0.166	0.053	0.085	0.057	-
C-683	1R	No	3.0	No	15.066	6.606	0.547	0.024	0.020	0.016	-
C-683	2L	No	2.7	No	14.390	17.638	14.783	8.205	2.989	1.098	-
C-683	2R	No	2.5	No	18.699	15.580	8.303	4.678	0.717	0.158	-
C-683	2R(2)	Yes	2.5	No	20.177	18.334	8.679	-	-	-	-
C-684	1L	No	3.0	No	1.357	2.819	10.287	5.605	1.450	0.105	-
C-684	1R	No	2.4	No	15.046	27.718	20.400	13.932	10.469	6.030	-
C-684	2L	No	2.7	No	31.007	17.379	8.671	1.397	-	-	-
C-684	2R	No	3.6	No	2.288	0.660	13.426	15.350	8.979	2.462	-
C-685	1L	No	2.7	No	11.502	13.977	5.318	0.522	0.182	0.194	-
C-685	1R	No	2.4	No	20.772	24.077	12.369	5.346	1.008	0.203	-
C-685	2L	No	2.6	No	11.206	18.679	12.915	6.658	0.753	0.130	-
C-685	2R	No	2.8	No	12.016	16.135	8.663	2.709	0.109	0.000	-
F-403	1L	No	2.3	No	22.895	15.714	1.620	0.636	0.531	0.709	-
F-403	1R	No	2.3	Yes	23.304	17.156	2.940	0.320	0.259	0.259	-
F-403	2L	No	2.5	No	20.732	25.855	16.014	2.309	0.595	0.693	-
F-403	2R	No	2.6	No	34.461	16.350	18.614	19.853	20.525	7.962	-
F-439	1L	No	2.5	No	29.849	23.373	16.026	8.157	0.721	0.223	-
F-439	1R	No	2.7	Yes	20.453	14.386	8.618	1.863	0.004	0.000	-
F-439	2L	No	2.1	No	40.488	18.468	8.290	2.410	0.194	0.134	-
F-439	2R	No	2.4	No	17.375	1.592	0.178	0.182	0.203	0.194	-
F-494	1L	No	2.0	No	35.786	27.969	13.900	6.816	2.434	0.126	-
F-494	1R	No	2.3	No	35.304	23.765	12.320	4.370	0.818	0.288	-
F-494	2L	No	1.7	No	35.632	28.601	15.163	6.014	1.584	0.223	-
F-494	2R	No	1.9	Yes	36.009	21.959	11.016	4.540	1.296	0.186	-
F-494	1L(2)	Yes	2.0	No	32.991	19.059	8.967	5.609	0.000	0.000	-
F-495	1L	No	2.1	No	5.095	2.511	8.371	1.790	0.996	0.089	-
F-495	1R	No	2.5	Yes	46.778	10.599	3.795	0.814	0.170	0.170	-
F-495	2L	No	2.0	No	37.625	21.562	8.598	2.385	0.227	0.069	-
F-495	2R	No	2.2	No	35.276	17.245	7.363	1.661	0.041	0.000	-
C-754	87-22	No	2.1	No	32.471	16.160	8.072	3.382	-	-	-
C-754	36-40B	Yes	2.8	No	30.980	17.921	7.325	-	-	-	-
C-754	29-3	No	1.5	Yes	35.936	27.378	17.715	13.989	-	-	-
C-754	174-39	No	1.8	No	26.704	18.310	12.112	7.418	-	-	-
C-754	36-40	No	2.7	No	27.643	13.084	3.878	0.344	-	-	-

C-754	72-14	No	1.7	No	22.546	7.081	0.753	0.176	-	-	-
C-754	203-11	No	0.6	Yes	7.758	11.198	8.953	6.579	-	-	-

Table A-11: Detailed Bridge Deck Data (Continued)

Deck ID	Test Loca-tion	Above Bar (Yes/No)	Cover Depth (in.)	Delam-ination (Yes/No)	Chloride Concentration (lb Cl^-/yd^3 of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
C-754	29-3B	Yes	1.3	Yes	29.664	-	-	-	-	-	-
C-725	1	Yes	2.9	No	12.146	16.676	14.007	11.338	-	-	-
C-725	2	No	2.5	Yes	15.439	25.788	16.771	13.175	-	-	-
C-725	3A	No	3.1	Yes	7.282	10.662	8.023	4.696	-	-	-
C-725	4A	No	2.2	No	8.226	8.558	5.081	3.637	-	-	-
C-725	5A	No	2.8	Yes	18.472	25.171	14.665	7.871	-	-	-
C-725	5C	Yes	2.8	Yes	21.939	17.611	13.916		-	-	-
C-725	7	No	2.5	No	18.618	17.241	5.901	2.408	-	-	-
C-725	8	Yes	2.5	No	21.720	22.320	10.800		-	-	-
C-725	3B	No	3.1	Yes	3.748	5.656	6.265	5.441	4.682	4.704	3.414
C-725	4B	No	2.2	No	8.209	6.840	5.158	3.914	3.406	3.114	3.139
C-725	5B	No	2.8	No	28.844	25.385	19.802	13.503	8.829	5.119	2.975
C-725	6A	No	2.5	No	13.114	19.900	15.269	11.449	-	-	-
C-725	6B	No	2.5	No	11.036	13.466	12.476	6.776	1.776	0.251	0.217
C-757	1	Yes	2.5	-	15.086	19.290	10.089	-	-	-	-
C-757	2	No	2.9	-	25.276	18.101	12.450	20.220	-	-	-
C-757	3A	No	3.3	-	45.283	19.199	11.164	7.922	-	-	-
C-757	4	No	3.3	-	17.646	22.544	18.916	13.227	-	-	-
C-757	5	No	4.0	-	14.730	16.690	14.517	9.345	-	-	-
C-757	6A	No	3.5	-	21.963	21.544	14.641	11.919	-	-	-
C-757	7	No	3.4	-	14.317	20.120	16.949	9.827	-	-	-
C-757	8	Yes	3.0	-	14.629	19.343	15.819	8.507	-	-	-
C-757	6B	No	3.5	-	58.081	30.881	15.232	11.976	9.888	9.831	11.50
C-759	1	Yes	3.6	-	7.355	12.893	11.453	6.557	-	-	-
C-759	2	No	3.4	-	6.294	12.407	10.951	8.884	-	-	-
C-759	3	No	3.0	-	50.617	25.434	9.971	5.589	2.659	0.763	0.249
C-759	4	No	3.1	-	8.465	15.522	13.521	10.607	-	-	-
C-759	5	No	3.1	-	6.954	15.293	10.886	8.687	-	-	-
C-759	6	No	3.0	-	14.633	12.875	9.647	6.194	3.366	1.126	0.429
C-759	7	No	2.0	-	7.120	14.805	10.532	4.722	-	-	-
C-759	8	Yes	2.0	-	30.262	11.668	12.209	-	-	-	-
C-760	1	Yes	1.5	No	30.197	25.335	-	-	-	-	-
C-760	2	No	2.6	No	34.753	18.610	8.606	2.847	2.264	-	-
C-760	3A	No	2.5	No	28.743	30.573	28.206	14.422	8.586	-	-
C-760	4	No	2.0	No	32.971	23.172	16.690	7.268	4.528	-	-
C-760	5	No	1.9	No	20.497	23.036	15.426	15.426	11.196	9.092	-
C-760	6A	No	2.4	Yes	33.720	33.289	25.343	21.817	16.131	-	-
C-760	7	No	2.2	No	59.701	43.019	34.399	16.022	8.708	-	-
C-760	8	Yes	2.3	No	60.118	37.740	45.621	-	-	-	-

C-760	3B	No	2.5	No	31.930	20.649	5.611	0.802	0.186	-	-
C-760	6B	No	2.4	No	43.070	35.630	29.620	21.562	11.079	3.967	-
C-931	1	Yes	3.3	No	2.369	1.580	0.500	0.261	-	-	-

Table A-12: Detailed Bridge Deck Data (Continued)

Deck ID	Test Loca-tion	Above Bar (Yes/ No)	Cover Depth (in.)	Delam-ination (Yes/ No)	Chloride Concentration (lb Cl^-/yd^3 of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
C-931	2	No	2.8	No	2.616	0.605	0.318	0.172	-	-	-
C-931	3	No	2.7	No	3.469	1.310	0.298	0.290	0.180	0.184	0.196
C-931	4	No	2.7	No	1.847	0.215	0.012	0.038	-	-	-
C-931	5	No	2.6	No	6.176	0.792	0.298	0.273	-	-	-
C-931	6	No	2.7	No	6.051	2.114	0.207	0.265	0.239	0.227	-
C-931	7	No	2.7	No	28.184	1.278	0.134	0.170	-	-	-
C-931	8	Yes	3.0	No	4.868	4.680	0.755	-	-	-	-
C-953	2	No	5.2	No	6.796	2.537	0.229	0.279	-	-	-
C-953	3	No	4.0	No	13.946	4.967	0.395	0.298	0.306	0.314	0.308
C-953	4	No	2.9	No	3.031	7.401	6.616	2.019	0.330	0.225	0.194
C-953	5	No	2.9	No	9.781	13.608	7.663	6.209	-	-	-
C-953	6	No	3.6	No	13.555	5.261	0.668	0.209	0.196	0.170	0.196
C-953	7	No	4.1	No	3.892	3.649	0.269	0.182	-	-	-
F-562	1	Yes	1.5	No	41.784	29.257	-	-	-	-	-
F-562	2	No	1.8	No	35.591	31.136	1.673	0.144	-	-	-
F-562	3	No	1.9	No	37.007	24.002	11.950	3.736	0.652	0.253	0.247
F-562	4	No	2.8	No	47.828	26.554	9.532	2.803	2.232	1.428	-
F-562	5	No	2.9	No	45.309	22.164	6.620	1.507	0.277	0.225	0.219
F-562	6	No	2.1	No	32.975	16.961	5.909	1.626	0.271	0.160	0.160
F-562	7	No	3.1	No	41.346	20.993	0.452	0.109	-	-	-
F-562	8	Yes	3.3	No	58.271	27.550	0.486	0.209	-	-	-
F-738	1	Yes	3.6	No	2.151	0.601	0.134	0.243	-	-	-
F-738	2	No	3.5	No	2.102	0.662	0.239	0.249	-	-	-
F-738	3	No	3.0	No	3.035	1.104	0.101	0.061	0.079	0.073	0.057
F-738	4	No	2.9	No	3.114	0.514	0.237	0.255	-	-	-
F-738	5	No	3.4	No	4.005	1.334	0.298	0.253	-	-	-
F-738	6	No	3.1	No	2.223	0.749	0.109	0.198	0.194	0.223	0.279
F-738	7	No	4.0	No	2.244	0.362	0.194	0.152	-	-	-
F-799	1	Yes	3.1	No	14.665	3.860	0.729	-	-	-	-
F-799	2	No	2.9	No	15.860	6.923	1.375	0.213	-	-	-
F-799	3	No	2.3	No	23.105	8.469	0.591	0.024	0.016	0.022	0.014
F-799	4	No	2.3	No	22.789	3.858	0.182	0.014	-	-	-
F-799	5	No	2.4	No	25.260	6.484	0.200	0.308	-	-	-
F-799	6	No	2.2	No	21.645	7.499	0.324	0.128	0.156	0.267	-
F-799	7	No	2.7	No	19.266	5.739	0.166	0.668	-	-	-
F-799	8	Yes	3.5	No	22.409	7.130	2.456	1.723	-	-	-
F-800	1	Yes	3.6	No	12.976	2.132	0.099	0.142	-	-	-
F-800	2	No	3.2	No	11.295	2.280	0.381	0.132	-	-	-
F-800	3	No	3.6	No	14.132	6.004	1.148	0.223	0.101	0.150	0.231

F-800	4	No	3.0	No	15.281	2.519	0.160	0.105	-	-	-
F-800	5	No	3.0	No	15.410	1.411	0.089	0.119	-	-	-
F-800	6	No	2.9	No	7.825	2.770	0.168	0.071	0.028	0.004	0.010

Table A-13: Detailed Bridge Deck Data (Continued)

Deck ID	Test Loca-tion	Above Bar (Yes/ No)	Cover Depth (in.)	Delam-ination (Yes/ No)	Chloride Concentration (lb Cl^-/yd^3 of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
F-800	7	No	2.7	No	18.509	2.916	0.111	0.103	-	-	-
F-800	8	Yes	2.9	No	20.116	3.195	0.134	-	-	-	-
C-525	283-8N	No	2.9	Yes	1.223	1.895	4.212	5.229	3.438	2.122	-
C-655	343-12S	No	3.4	No	7.863	4.352	1.978	1.085	0.466	0.257	-
C-525	405-14N	No	3.1	-	15.137	9.196	4.781	2.709	1.938	1.401	-
C-655	533-5S	No	4.3	No	5.451	2.138	0.395	0.279	0.277	0.320	-
C-525	706-3N	No	4.0	-	4.400	2.193	1.624	1.379	0.352	0.075	-
C-655	989-11S	No	3.4	No	5.139	1.924	0.186	0.109	0.209	0.138	-
C-655	1163-12S	No	3.7	No	2.110	0.215	0.113	0.085	0.101	0.130	-
C-655	1340-10S	No	3.7	No	12.470	8.015	4.502	2.181	0.699	0.186	-
C-655	1351-14N	No	3.5	No	10.518	3.665	0.219	0.192	0.176	0.148	-
C-655	1402-13N	No	3.6	No	6.687	6.241	4.870	3.924	4.131	4.313	-
C-655	1821-17S	No	3.9	-	3.732	4.093	3.501	2.497	1.537	0.672	-
C-655	1932-9N	No	3.3	No	2.728	1.590	1.403	1.899	1.849	1.418	-
C-655	2329-11S	No	3.2	No	2.869	1.108	0.174	0.093	0.073	0.158	-
C-525	2565-14S	No	3.5	-	8.926	7.363	7.594	7.547	4.791	1.624	-
C-525	2575-1S	No	3.1	-	7.268	4.259	3.094	3.011	2.764	-	-
C-655	2731-6N	No	3.6	No	10.018	3.558	0.223	0.119	0.095	0.077	-
C-655	2908-15N	No	3.5	No	7.606	4.350	2.560	2.335	1.770	0.861	-
C-525	3093-14S	No	3.2	-	8.102	5.368	2.835	0.942	0.178	0.168	-
C-655	3288-12N	No	3.7	No	1.087	0.565	0.332	0.292	0.172	0.188	-
C-1036	NE	No	3.225	No	1.458	0.228	-	-	-	-	-
C-1036	NW	No	3.775	No	0.373	0.173	-	-	-	-	-
C-1036	SE	No	3.075	No	0.356	0.149	-	-	-	-	-
C-1036	SW	No	2.575	No	0.340	0.109	-	-	-	-	-
F-862 (NB)	NE	No	3.1625	No	0.429	0.255	-	-	-	-	-

F-862 (NB)	NW	No	2.7	No	0.514	0.343	-	-	-	-	-

Table A-14: Detailed Bridge Deck Data (Continued)

Deck ID	Test Location	Above Bar (Yes/No)	Cover Depth (in.)	Delamination (Yes/No)	Chloride Concentration (lb Cl^-/yd^3 of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
F-862 (NB)	SE	No	3.225	No	0.332	0.273	-	-	-	-	-
F-862 (NB)	SW	No	2.775	No	0.186	0.143	-	-	-	-	-
F-866 (SB)	NE	No	3.25	No	2.390	2.471	-	-	-	-	-
F-866 (SB)	NW	No	3.2125	No	1.883	0.310	-	-	-	-	-
F-866 (SB)	SE	No	2.825	No	0.559	0.289	-	-	-	-	-
F-866 (SB)	SW	No	3.225	No	0.361	0.292	-	-	-	-	-
C-1035	NE	No	3.0125	No	1.219	0.125	-	-	-	-	-
C-1035	NW	No	3.1	No	0.356	0.122	-	-	-	-	-
C-1035	SE	No	3.1125	No	0.389	0.188	-	-	-	-	-
C-1035	SW	No	2.9375	No	0.356	0.125	-	-	-	-	-
C-752	16	No	3.72	-	14.460	4.812	2.688	0.651	0.185	0.245	0.181
C-752	28	No	3.483	-	18.890	3.415	0.195	0.225	0.207	0.183	0.141
C-752	63	No	3.3075	-	22.323	8.148	1.115	0.749	0.740	0.766	0.717
C-752	79	No	2.23	-	13.900	0.757	0.251	0.206	0.171	0.179	0.124
C-752	92	No	2.58	-	17.780	1.993	0.201	0.228	0.232	0.164	0.172
C-752	104R	No	2.394	-	8.608	0.333	0.190	0.187	0.174	0.134	0.110
C-759	10	No	2.9665	No	19.561	12.742	6.804	3.795	1.479	0.350	0.095
C-759	18	No	3.1345	No	13.376	9.585	5.690	2.910	0.871	0.055	0.023
C-759	35	No	3.618	No	13.199	9.397	5.767	2.877	1.030	0.489	0.775
C-759	44	No	2.8475	No	11.152	8.575	5.065	2.257	0.419	0.155	0.072
C-759	52	No	3.185	No	19.722	12.620	7.221	3.868	1.645	0.769	0.070
C-759	59	No	2.3375	No	14.662	9.293	5.873	3.238	1.408	0.376	0.085
F-53	1	Yes	2.4	-	0.405	0.290	0.531	-	-	-	-
F-53	2A	Yes	2.8	-	2.535	1.646	1.183	-	-	-	-
F-53	2B	No	-	-	0.729	0.401	0.431	0.290	-	-	-
F-53	3	No	-	-	0.790	0.490	0.360	0.322	0.281	0.022	0.529
F-53	4	No	-	-	5.285	0.620	0.346	0.215	-	-	-
F-53	5	No	-	-	1.887	0.421	0.249	0.196	-	-	-
F-53	7	No	-	-	0.547	0.350	0.415	0.411	-	-	-
F-53	8	Yes	1.1	-	0.344	0.156	-	-	-	-	-
C-736	12	No	2.742	-	14.241	5.675	0.628	0.118	0.064	0.332	0.687
C-736	24	No	3.1745	-	19.189	6.764	0.179	0.081	0.070	0.068	0.080
C-736	47A	No	2.9515	-	20.394	6.017	0.611	0.161	0.099	0.081	0.075
C-736	59	No	2.8675	-	14.810	4.114	0.758	0.433	0.054	0.028	0.009

C-736	68	No	3.1935	-	13.827	4.062	0.150	0.055	0.045	0.037	0.032
C-736	78	No	3.122	-	13.822	3.243	0.157	0.095	0.042	0.048	0.032

Table A-15: Detailed Bridge Deck Data (Continued)

Deck ID	Test Location	Above Bar (Yes/ No)	Cover Depth (in.)	Delamination (Yes/ No)	Chloride Concentration (lb Cl^-/yd^3 of Concrete) at Specified Cover Depth (in.)						
					0.5 (in.)	1.5 (in.)	2.5 (in.)	3.5 (in.)	4.5 (in.)	5.5 (in.)	6.5 (in.)
C-460	1	Yes	2.5	-	27.540	9.696	-	-	-	-	-
C-460	2	No	-	-	-	13.246	6.239	2.116	-	-	-
C-460	3	No	-	-	13.211	13.487	10.852	6.583	3.141	0.221	0.200
C-460	4	No	-	-	11.482	23.751	15.627	8.639	-	-	-
C-460	5	No	-	-	13.183	20.862	14.493	9.311	-	-	-
C-460	7	No	-	-	9.064	12.879	10.919	6.634	-	-	-
C-460	8	No	-	-	10.409	10.641	8.675	7.252	-	-	-
C-698	1	Yes	2.8	-	12.806	20.529	20.590	-	-	-	-
C-698	2	No	-	-	10.283	21.416	18.697	15.315	-	-	-
C-698	3	No	-	-	9.949	13.493	14.130	9.252	3.554	-	-
C-698	4	No	-	-	15.188	24.889	21.392	13.968	-	-	-
C-698	5	No	-	-	5.362	12.055	12.492	13.231	-	-	-
C-698	7	No	-	-	40.492	26.809	12.482	6.484	-	-	-
C-698	8	Yes	3.1	-	21.663	13.806	-	-	-	-	-
C-794	1	Yes	3.4	-	0.583	0.209	0.194	0.164	-	-	-
C-794	2	No	-	-	0.073	0.154	0.099	0.093	-	-	-
C-794	3A	Yes	3	-	1.897	4.429	3.161	2.068	-	-	-
C-794	4	No	-	-	0.373	0.095	0.081	0.117	-	-	-
C-794	5	No	-	-	0.494	0.174	0.089	0.045	-	-	-
C-794	6	No	-	-	4.581	3.187	1.604	0.417	0.093	0.073	0.057
C-794	7	No	-	-	3.050	3.232	1.486	0.324	-	-	-
C-794	8	Yes	2.7	-	0.547	0.200	0.109	-	-	-	-
F-476	1	Yes	3.5	-	6.974	4.574	2.695	0.901	-	-	-
F-476	2	No	-	-	9.627	6.905	4.528	2.084	-	-	-
F-476	3	No	-	-	22.546	22.514	20.363	15.495	10.514	7.189	5.954
F-476	4	No	-	-	7.444	7.328	6.241	4.331	-	-	-
F-476	5	No	-	-	12.895	9.471	8.505	6.269	-	-	-
F-476	6	No	-	-	24.630	20.058	16.567	13.316	9.811	7.608	6.071
F-476	7	No	-	-	4.807	4.198	3.240	2.701	-	-	-
F-476	8	Yes	1.5	-	4.427	-	-	-	-	-	-